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U. S. COAST GUARD LIGHTWEIGHT FIRE-FIGHTING MODULE

Final Report

Prepared for
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812
(Contract No. NAS8-31977)

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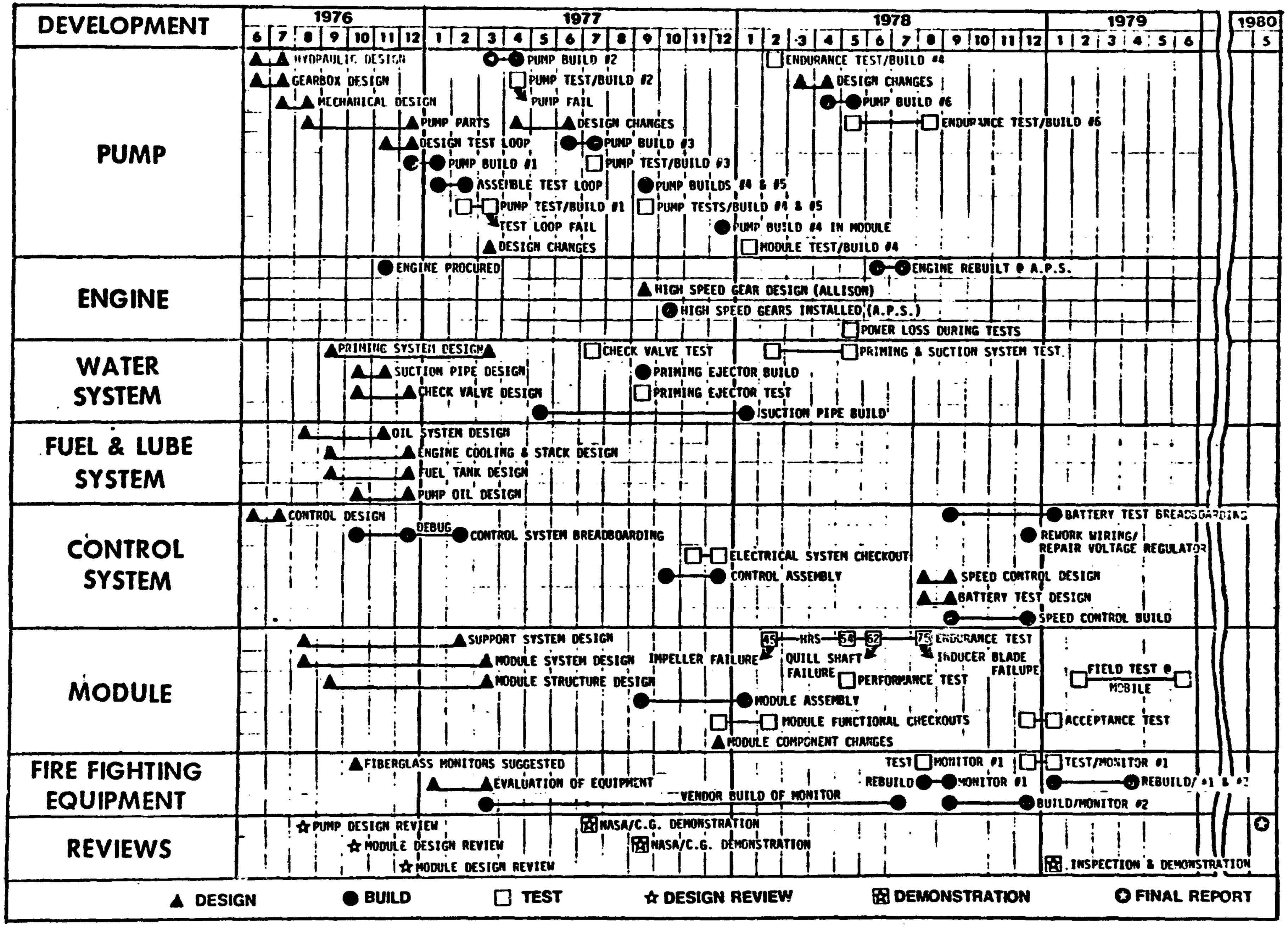
INTRODUCTION

The U. S. Coast Guard Fire-fighting Module has been developed by Northern Research and Engineering Corporation (NREC) under contract to NASA and USCG for the purpose of fighting fires in harbors and on ships. The module can be lifted by a dockside crane or helicopter and placed on the deck of a patrol boat or cutter for transportation to the scene of the fire. At the fire the module can be set up and put in operation by a crew of two in approximately fifteen minutes. Once in operation the module will deliver water to two fire nozzles at a pressure of 150 psi and a flow rate of 2000 gpm. Sufficient fuel is carried in the module for three hours of continuous operation. A photograph of the fire-fighting module in operation is reproduced in Figure 1.

This report presents a historical record of the development of the NREC fire-fighting module. The initial design concepts to final working module are arranged in chronological order to document milestones of progress made. A development summary of the NREC fire-fighting module project is provided on the next page.

Three other reports have been issued by NREC and form part of the documentation of the U. S. Coast Guard Fire-fighting Module: NREC Report No. 1296-2 (Operating and Routine Servicing Manual); No. 1296-3 (Maintenance and Spare Parts Manual) and No. 1296-4 (New Technology Report).



FIRE-FIGHTING MODULE DEVELOPMENT SUMMARY

DESCRIPTION

The Module and its Equipment

The fire-fighting module is a rectangular unit measuring 6 ft wide, 5 ft deep, and 4 1/2 ft in height. The module contains a gas turbine engine, a water pump, fuel and oil tanks, a control system, batteries, and fire-fighting equipment.

This description of the module will refer to figures at the back of this manual. These figures are made from photographs and show the various parts of the module and its equipment.

Figure 2 is a view of the front and right side of the module as it looks with all the equipment stored inside and the doors closed. The fuel tank forms the base of the module. On the front of the module is a large double door for access to fire-fighting equipment. On the top are the two doors that cover the control panel and the engine exhaust ports. On the right end are doors for access to the booster hose, the fire suits, and the engine compartment. One of the two water discharge pipes is located on the right end of the module; it is covered with a Storz end cap. Also on the right end is a shore power connection (115 Vac) for charging the batteries; a 50-ft electrical cable is supplied. Lifting eyes are located at the four top corners of the module; a lifting sling is provided. The module may also be lifted with a forklift at the tunnels located near the bottom on each end. On the top of the module there is a monitor base pad on which one of the fire-fighting monitors contained in the module can be mounted.

Figure 3 is a view of the rear and left end of the module. The suction pipe storage rack on the back of the module holds the suction pipe elbow and three straight sections, with clamps attached. On the left end are the second water discharge pipe, the water inlet (where the suction pipe is connected during operation), and the fuel filler pipe. Two of the four hold-down rings attached to the fuel tank are shown in this view.

Figures 4 and 5 show views of the module with the doors open that would normally be open during operation. In Figure 4 the control panel, oil cooler, and engine exhaust openings can be seen. The air inlet door (open) is seen in Figure 5.

Figure 5 shows the storage of fire-fighting equipment in the main storage compartment (behind the large front doors). The equipment stored here includes:

. four 25-ft lengths of fire hose, 4 in diameter
. two monitors
. two straight stream nozzles
. one fog/foam nozzle
. one foam injector
. two shutoff valves
. spanner wrench for Storz couplings
. two adapters for 4 in Storz to 2 1/2 in threaded coupling

Figure 7 shows the fire-fighting module set up to fight a fire, with the inlet suction pipe, water hoses, valves, monitors, and nozzles deployed. Other equipment that is included in the module is shown in the foreground of the photograph.

Figure 8 shows the control panel at the top right corner of the module. On this panel are the various gauges and lights that indicate conditions in the pump, engine, and control system. The main power switch is in be center of the panel and the control level at the upper right side.

Figure 9 shows the inside of the module with the cover removed. The engine is a 346 hp Allison gas turbine. The pump is a two-stage centrifugal. Water enters the pump inlet (at the right in the photograph) and leaves through the check valve, where it splits into two streams and exits the module through the two discharge pipes. The primer is mounted on the pump.

Figure 10 shows a typical suction pipe assembly.

Module Operation

Figure 11 is a schematic diagram of the module and its equipment in operation. The operator controls module operation by moving the control lever on the control panel (Fig 8). The control system automatically starts the engine, primes the pump, and brings the engine speed up to the selected value. Seawater is drawn through the suction pipe into the pump. It is discharged through the check valve into the water manifold (discharge pipes).

Four inch hoses connect the discharge pipes to the two monitors, where the water leaves through two nozzles.

Dolly (Trailer)

A special dolly (trailer) is provided with the module (Fig 12). The dolly may be used to transport the module to dockside for transfer to a patrol boat. Alternatively, the module may be operated directly from the dolly at the scene of the fire. The module may be lifted onto the dolly by forklift or crane. It is expected that the module will normally be stored on the dolly.

The module must always be placed on the dolly with the water inlet facing rearward as shown in Figure 12, so that the suction pipe can be installed with the module mounted on the dolly. The module must be secured to the dolly during transportation, operation, or storage; tie-down straps and eyes are provided.

The dolly is equipped with a 2 in ball trailer hitch positioned approximately 18 in above ground level, safety chains, surge brakes, and running lights. Two jack strands at the rear and a crank-operated jack at the front stabilize the dolly when not attached to a vehicle. These jacks must be grounded if the module is to be operated or stored while mounted on the dolly.

DEVELOPMENT HISTORY

Introduction

In this section of the report the development of the fire-fighting module and its component parts is recorded chronologically. The record is broken down by major components into seven subsections having to do with, respectively, the pump, the engine, the water system, the fuel and lubricating systems, the control system, the module structure, and the fire-fighting equipment.

Pump Development

Hydraulic Design

The development of the pump began in June, 1976 with hydraulic design of the two individual stages and their matching. Because of design iterations required for successful matching, the hydraulic design of the pump took longer than anticipated. The successful operation of a two-stage pump depends not only on the performance of the individual stages, but also upon the matching of the stages. Both the inducer and the pump were based on previous NREC designs, but the two were independent. Upon detailed investigation it was found that there was a serious mismatch between them, in that the velocity at the discharge from the inducer impeller was considerably higher at design point than the velocity at the pump inlet. This required an excessive amount of diffusion in the interstage stator and would have penalized the over-all pump efficiency. For this reason a considerable amount of redesign work was required to achieve an inducer impeller design that would produce the correct exit velocity. This caused an initial slippage in the program schedule.

Hydraulic design of the pump was completed in July 1976. Computer analysis of the flow path predicted that the design objectives of 408 ft head rise, 2000-2200 gpm flow rate, and 12-20 ft suction lift would be met at a pump speed of 6315 rpm. Specifications for the flow path dimensions of the inducer impeller, interstage diffuser, main impeller, vaned diffuser, and volute and discharge pipe were made available for detailed mechanical design and drafting.

Gearbox Design

The detailed design of the pump interstage gearbox was carried out in June and July of 1976. To meet loading and life requirements within the small space envelope availabel it was decided to use three planet gears instead of one.

Pump Mechanical Design

Mechanical design of the pump was carried out from late July through September of 1976. Materials were selected, stresses, dimensions, and tolerances were computed. Bearings and seals were designed. Oil flow requirements were determined. Oil supply and drain passages were located and sized. Surface treatments and coatings for parts exposed to salt water were investigated. Detailed drawings of pump parts were prepared.

Pump Design Review

A meeting was held at NREC on August 10, 1976 for the purpose of reviewing hydraulic and mechanical design of the pump. Representatives of NASA and the U. S. Coast Guard participated in this design review. Items discussed, involving the pump only, included:

1. Hydraulic design and performance
   a. component performance
   b. system performance
   c. comparison of design with proposal
2. Pump layout and mechanical design
   a. design features
   b. materials
   c. bearings
   d. gears
   e. seals
   f. weight and envelope
   g. contaminant ingestion

The design was found to be satisfactory in general. Two material changes were recommended by NASA/Coast Guard and were incorporated into the design. They were:

1. Use of aluminum A356-T6 instead of 356-T6.
2. Use heat treat on 17-4PH greater than 1000 deg F.

First Pump Parts Received

A sample impeller casting was received in September, 1976 and was found to be adequate. Seals and bearings were received. Machining vendor work began work on shafts and other parts.

Design Review

A meeting was held at NREC on October 14, 1976 for the purpose of reviewing the design of the pump and module. Representatives of NASA and the U. S. Coast Guard participated in the design review. Items discussed, involving pump only, included:

1. Pump mechanical design
   a. requirements for assembly, disassembly, and maintenance are to be documented by NREC
   b. special tools for assembly, disassembly are to be provided with module
2. Water separator - NREC reported on its effort to solve the potential problem of seawater entering the engine and pump lubrication oil through the pump seals.
   a. no suitable water separator has been found available commercially
   b. NREC recommended a separate lubrication system for the pump, either an internal splash system or a circulating system with an engine-driven pump.

   It was decided that a separate circulating pump-lubrication system should be designed, and that the cost of extra components should be added to the contract price.

Pump Parts Procurement, Inspection, and Assembly

Procurement of parts for the initial build of the pump commenced in September, 1976 and continued through December. Except for the castings of the inducer impeller and the inducer housing, this was a fairly routine procurement. Castings of the inducer impeller and housing were delayed by tooling

development problems. Each of these castings was geometrically complex and the tooling was difficult to design and to apply. Changes in both the tooling vendor and the foundry were necessary before a satisfactory combination was found. An interim method for casting the inducer housing was implemented to speed up delivery of the first prototype casting. This method involved casting the housing in two sections that were subsequently welded together. This approach produced a housing that was mechanically sound but had some roughness and blockage in the hydraulic passages. This housing was used in the first pump builds (Builds 1 and 2). A satisfactory one-piece housing was first available in May, 1977.

Assembly and instrumentation of the first build of the pump was started in December, 1976 and completed in January, 1977.

Pump Test Plan

A test plan for performance and endurance testing was prepared (NREC 1296 Memorandum M1, dated December 9, 1976). This test plan described test procedures and instrumentation for performance tests and 10[illegible] endurance tests. The pump, inducer, and assembly test series were combined with inter-stage instruments to provide information on component performance.

Design Review

A meeting was held at NREC on December 15, 1976 for the purpose of reviewing the design of the module and the test plan. The test plan was found acceptable.

Pump Performance Tests - Build No. 1

During February 1977 three performance tests were run. Sufficient test data was obtained to determine head-flow characteristics at half speed (3150 rpm), inlet pressure at atmospheric. The initial runs served to debug the newly installed water-flow test loop. Several problems with valves, flowmeters, and leakage were discovered and corrected.

Pump testing continued into march. Pump tests were run at half speed (3150 rpm), 3/4 speed (4500 rpm) and full speed (6315 rpm). At full speed, a flange in the test loop failed. One data point was obtained at full speed

prior to the failure. This data point showed that the pump flow rate was 15 per cent short of the design goal. Detailed analysis of the data showed that the NPSH requirement of the main impeller was not being met.

Pump Teardown and Rebuild

Pump and test loop were disassembled and improvements made to increase performance of the pump and test loop. Significant pump modifications made were:

1. Cracks between the trailing edges of inducer stator vanes and shroud were filled to reduce leakage.
2. Leading edges of main impeller blades were filed on the suction sides to improve inlet incidence angle.
3. Clearance at main impeller shroud was reduced to 0.010 in (design value).

Pump Performance Tests - Build No. 2

Pump and test loop modifications were completed and both reassembled. Pump tests were run at speeds from 4500 to 5700 rpm. Data was scaled to full speed (6135 rpm). Results showed that the flow rate was a few per cent off the 2200 gpm design goal.

Flow Sensor Error

Checks were made to test circuit to determine accuracy of data. One of three flow meters was found to be reading lower than the other two when connected to the same input source. The low reading meter was then switched with correct reading one. From observation, there was a substantial increase in head rise from the March test to the April test. Because of inaccurate readings obtained in March, it could be inferred that the flow rate had improved also. Flow sensors were sent to Alden Hydraulic Laboratory in Holden, Mass. in May for calibration.

Air Bubble Removal

Attempts to remove air bubbles from the test loop were not very sucussful at this stage of testing. The presence of air bubbles (1 to 2 per cent

at this stage) reduced pump performance, hence flow radings were less than expected.

Pump Failure, Teardown and Rebuild

On April 20 a pump failure occurred. Upon disassembly, it was found that the pump spline coupling had been installed wrong. Several parts were damaged as a result of this mishap. Replacement parts were ordered and several modifications to the flow path were introduced at this time. These improvements were as follows:

1. Impeller blades were made thinner and longer. This was to produce an increase in head and smaller wakes at impeller discharge.
2. Inducer housing cast in one piece. This was to produce smoother interstage diffuser passages with less blockage and tendency to flow separation.
3. Shroud diameter increased at inlet of main impeller. This was to reduce NPSH requirement of the main impeller.
4. Main impeller backslope reduced. This was to increase discharge pressure and make head-flow characteristic steeper.
5. The visco seals were replaced by carbon running-ring seals.

A sample one-piece inducer housing was received from the casting vendor. This first unit was porous in several places, but the porosity was eliminated by welding and epoxy filling. This housing was substituted for the original two-piece housing in the next pump build.

Pump Performance Tests - Build No. 3

The pump was reassembled in July, 1977 with new machined parts. It was then tested at 5500 and 6300 rpm (full design speed). Pump performance dropped slightly from performance at Test No. 2 in April. This was thought to be caused by excessive shroud clearance due to machining errors. The pump was demonstrated for NASA and Coast Guard representatives on July 26 and 27.

Pump Performance Tests - Builds No. 4 and 5

Two pumps were assembled and tested in early September, 1977. The test of Build No. 5 was witnessed by NASA representatives on September 8.

Both pumps fell short of the performance goal of 408 ft head rise at 2200 gpm. Pump Build No. 4 was chosen to be installed in the Coast Guard module.

Engine Gear Change to Increase Pump Speed

In September, 1977 it was decided to retrofit the Allison engine with a new output shaft gearset. With this change the pump speed will be 6600 rpm instead of the original 6315 rpm. The purpose of this change was to improve the pump head and flow rate.

This change was implemented in October, 1977.

Installation of Pump in Module

The pump (Build 4) and the engine with high-speed (6600 rpm) gears were installed in the fire-fighting module in December, 1977.

Performance Tests - Pump (Build 4) in Module

In January, 1978 module performance testing was started. Three tests were run in salt water, one on freshwater. Pump performance of 186 psig discharge pressure and 2000 gpm at 10 ft suction lift was achieved at 6680 rpm. The flow rate was measured at the nozzles and was uncalibrated.

Endurance Tests - Pump Build No. 4

An endurance test program was started in February 6, 1978 and continued (with a one-week interruption because of the blizzard of 1978) until suspended on February 27 after 45 hours of running time. The endurance test was terminated because of pump leakage, performance degradation, and suspected main impeller blade failure.

Pump Teardown and Inspection

After suspension of the endurance test on February 27, the pump was disassembled and inspected. It was discovered that the main impeller had lost a 2 in segment of one blade tip through fatigue fracture and had suffered severe pressure-surface cavitation damage. Photographs of the main impeller are reproduced in Figure 13. The pressure-surface cavitation on the main

impeller is thought to be caused by negative incidence on the blades. This could in turn be caused by operation at excessive flow rates or, more likely, by distortions in the flow into the main impeller inlet due to upstream geometry and flow in the inducer stage. The lost impeller blade tip shows evidence of fatigue fracture. Another blade shows a small crack starting. Blade fatigue cracking could only occur under blade pressure loading not seen in normal operation. This excessive loading may be associated with the severe pressure-surface cavitation or, alternatively, with unbalanced peripheral pressure fields at low flow rates.

The inducer impeller showed slight suction-surface cavitation damage on one blade; the shape of the inlet of this blade had been changed by grinding (done to balance the impeller); this changed shape is thought to be responsible for the inducer cavitation damage; grinding at this location will be avoided in the future. Photographs of the inducer impeller are reproduced in Figure 14.

The bearings behind the main impeller had sustained heavy damage. The back bearing showed damage all around both inner and outer races, whereas the front bearing outer race showed damage only over the lower 180 degrees (with respect to pump orientation). The initial impression of this damage is that heavy loads, both radial and thrust, had been seen by the bearings.

Pump Design Changes

Several design changes to the pump were initiated in early March, 1978:

1. New gears were ordered. These were expected to increase the rotating speed of the inducer by 25 per cent. The speed change should increase the inlet head of the main impeller and improve its cavitation performance.
2. The diameter of the inlet of the main impeller was increased and the shroud line changed to match. This was expected to increase the flow capacity of the pump and improve its cavitation performance.
3. The bearings behind the main impeller were redesigned. A larger bearing with increased thrust capacity was chosen. This should increase bearing life.

Modified pump parts were procured and installed during April and May, 1978.

Performance and Endurance Tests - Build No. 6

Performance testing was resumed in late May, 1978. The flow/pressure calibration of the Stang nozzles was checked by a direct volumetric measurement of flow into a tank of known volume. The results indicate that the pump exceeds the flow requirements of 408 ft head at 2200 gpm, at a pump speed of 6315 rpm.

Endurance testing was continued until a quill shaft failure on June 6.

Pump Teardown and Inspection - Build No. 6

After the quill shaft failure the pump was removed from the module and partially disassembled for inspection. The spline teeth on the quill shaft were found to have failed at the engine end. The mode of failure suggested that misalignment was the cause. A longer shaft was fabricated and an improved alignment procedure was implemented to prevent recurrence.

Inspection of the impellers revealed cavitation damage to be setting in after the approximately 25 hours of running in performance and endurance tests. The damage to the main impeller consisted of polishing of the blade surface near the middle on the pressure surface and near the root on the suction surface; this polishing had proceeded far enough to remove the anodize coating, but had not yet developed cavitation pits. Cavitation damage to the inducer impeller occurred on the suction surface about 2 inches in from the leading edge; some pitting was observed in an area about the size of a quarter. Photographs of the cavitation damage are reproduced in Figures 15 and 16.

It was also found that one of the inducer blades was cracked over a distance of about 3 ins near the root. Both ends of the crack terminated in the blade; that is, the crack did not extend to the blade edge. This crack was weld repaired.

Both impellers were coated with polyurethane paint in the areas affected by cavitation, in an effort to slow down the cavitation damage in further testing.

The bearings, seals, gears, and other components of the pump appeared

to be in excellent condition upon inspection. The pump was reassembled and reinstalled in the module.

Endurance Tests - Build No. 6

After engine rework to replace damaged components (see Engine section), the engine was reassembled and endurance testing was continued in August, 1978. An additional 13 hrs of testing were accumulated. Two inducer blades cracked during this test series, forcing its suspension.

Inducer Blade Failure

Blades cracked on two inducers during the August endurance test series. Photographs of a failed blade are shown in Figure 17. The first inducer to fail had been run on the pump for a total of approximately 34 hrs. After the first 25 hrs (8 hrs performance plus 17 hrs endurance) a hairline crack near the blade root was observed. This crack did not extend to the edge of the blade. The blade was weld repaired and the inducer put back in service. A failure of the type shown in Figure 5 occurred after an additional 9 hrs of running (2 hrs performance plus 7 hrs endurance). The failure was located at the weld repair. The first inducer was then removed from the pump and replaced by a second inducer.

The second inducer had operated for approximately 55 hours on the pump in January and February, 1978, when the low-speed interstage gears were still installed in the pump. At the time of reinstallation it appeared to be in excellent condition with only minor cavitation damage on one blade. This inducer experienced a failure similar to that of the first inducer after an additional 6 hrs of endurance testing.

In both inducers the failure appears to have started as a small crack near the blade root at a location about three inches downstream of the leading edge of the blade. The crack then propagated along the hub and eventually out to the blade shroud edge about one-third of the way from the leading edge to the trailing edge.

Measurement of blade natural frequencies and analysis of the probable failure mechanism were undertaken. NREC decided that the gears should be changed in the pump and the inducer operated at the original lower speed, where it appeared to be capable of operating without failure.

A thorough investigation of the cause of inducer blade failure was completed in September. Experimental measurement of blade dynamics in air at the NREC laboratory showed natural frequencies at 164, 365, and 998 Hz. The first two of these frequencies correspond to four and eleven times the rotating frequency of the inducer at the normal speed of operation. As there is a significant energy component in the fourth harmonic and as there are eleven stator vanes downstream of the inducer, these two resonances may easily be excited. Examination of the blade root thicknesses showed that in the region of the fracture the blades were typically 0.11 to 0.12 ins thick, whereas the design thickness is 0.25 ins. This decrease in thickness causes a large increase in the stress at the root above the nominal design value. On the above basis, the steady-state root stress was estimated to be 23,000 psi and the vibratory stress 4,000 psi. For the aluminum A356 cast blades these stresses are high enough to cause rapid failure by fatigue cracking.

In an effort to refine the experimental measurement of resonant frequency, the acoustics research firm Bolt, Beranek and Newman was given a subcontract to measure the blade resonant frequencies in water. Their very detailed results show a number of fairly large resonances at 880 Hz and above and smaller ones at 760, 500, and 360 Hz. Dimensional limitations of their water tank and sound source rolloff prevented measurement of resonances below about 180 Hz. The NREC and BBN results were in partial agreement and further work at NREC was planned to resolve discrepancies. There was, however, agreement on the existence of a resonance near 360 Hz at the approximate frequency of the eleventh engine order associated with the stator vanes.

It was clear from the analysis that the inducer has been operating at high stress levels. There were two ways to reduce the stress:

1. Reduce the operating speed, to reduce the blade pressure loading and drop the excitation frequency below the resonant frequency.
2. Increase the thickness of the blades at the root to the design value or higher.

The first of these was implemented by replacing the high speed pump gears with the original low-speed gear set.

Material Change; Inducer Tooling Modification

At a meeting of representatives of NASA, USCG, and NREC on September 12-13, 1978, it was tentatively decided to procure a main impeller of titanium or Inconel and an inducer with strengthened blades. NREC would then undertake a 50 hr endurance test of the pump with these new components, refurbish the pump, conduct the Acceptance Test, and ship to the Coast Guard. NASA agreed to bear the cost of materials for the main impeller and the personnel costs would be covered by time allocated in the contract to module servicing.

This decision was later reversed because of the high cost of the titanium impeller.

Demonstration and Acceptance Test - Build No. 7

The pump was reassembled with low-speed gears and installed in the module for demonstration and acceptance testing in December, 1978 and January, 1979. The performance of the pump was judged acceptable. Detailed results of acceptance testing are reported elsewhere in this report.

Engine

The engine selected as the driver for the fire-fighting pump was an Allison Model 250-C20 manufactured by the Detroit Diesel-Allison Division of General Motors Corporation. A rebuilt engine was purchased in October, 1976 from Aviation Power Supply, Burbank, California. This engine had just completed testing and had been certified for industrial use.

The engine was used to drive the pump in tests at the NREC laboratory in February through September of 1977.

High Speed Gears

In September, 1977, after evaluating the performance of the pump as measured in tests at the NREC laboratory, NASA, USCG, and NREC personnel concluded that the pump should be run at higher speed to improve its performance. Aviation Power Supply, who were developing a commercial version of the fire fighting module incorporating the NREC pump, had persuaded Allison to design a replacement engine gear set to increase engine speed by 10 per cent

(from 6016 to 6600 rpm). It was decided that the higher-speed gears should be incorporated into the Coast Guard module as well. Accordingly, the engine was shipped to Aviation Power Supply in October, 1977 where a high-speed gear set was installed and engine performance was checked out.

Operation in Module; Power Loss

Upon its return to NREC, the engine was installed in the module. During endurance and performance testing in the module in early-middle, 1978 the engine repeatedly ingested salt water vapor and was flushed with fresh-water to return performance to normal.

The module was disassembled and reassembled several times during the first half of 1978. After reassembly in May, 1978, it was observed that engine power had deteriorated significantly below the manufacturer's specifications. This power shortage (approximately 50 hp) limited testing capability on hot days. This problem was discussed with APS and Allison personnel. The engine was partially disassembled at NREC. The compressor showed some evidence of corrosion on the back surfaces of the stators. The first stage turbine rotor ans stator were coated with deposits. These factors did not appear to be sufficient to explain the large power loss.

Other possible power-loss mechanisms were explored and dismissed. These included leakage, malfunctioning blowoff valve, thermocouple error or wiring.

Since the power loss was not satisfactorily explainable or repairable at NREC, the engine was sent back to APS for further inspection and repair.

Engine Testing, Inspection and Repair

The Allison 250-C20 engine was shipped at the end of June to Aviation Power Supply, Inc., in Burbank, California for inspection and possible repairs. The engine was tested in the APS test facility and found to deliver 302 hp at 1358 deg F turbine temperature (corrected to standard day conditions); this power was 12.7 per cent below the design power of 346 hp. The engine was then partially disassembled and the turbine stators and rotors were inspected. It was found that the first stage rotor blades were burned back about 0.030 to 0.060 in at the tips and that the pressure balance piston seal attached to the

second stage rotor was excessively worn because of warping in the static structure supporting the seal. In addition, the turbine tie bolt was stretched beyond tolerance and two bearings were excessively worn.

NREC then authorized the replacement of the first and second stage rotors, the tie bolts, and the bearings, and cleaning of the compressor and touch-up painting of the gearbox to stop corrosion. After APS had completed this work the engine was retested and found to give a power output of 354 hp at 1358 deg F turbine temperature (corrected to standard day), 2.3 per cent above design power. The engine was then (on July 28) shipped to NREC for reinstallation in the module.

It should be noted that the engine power was brought up considerably higher than when the engine was first received from APS in late 1976. At that time it tested 3.7 per cent below design power at 1358 deg F on the APS test facility. A later test at APS, in October, 1977 at the time when the high-speed gears were installed, also showed power 3.7 per cent low.

It was the opinion of APS personnel that the damage to the first stage turbine and the balance piston seal was caused by overtemperature, most likely on startup. Such overtemperature is usually caused either by lighting off at too low a speed or by too slow acceleration after lightoff. Slow acceleration is generally attributable to a weak battery. Such conditions may have occurred early in 1978 after module reassembly when control system and instrumentation problems prevented proper monitoring of lightoff speed and engine temperature during initial engine starts in the laboratory. NREC feels confident that the batteries are more than adequate and that the control system when fully operational will prevent hot starts. These elements were carefully monitored during all subsequent starts.

Water System

Priming Ejector

Design requirements for the priming ejector were established in September, 1976. Bleed air conditions for the engine at idle were obtained. Detailed calculations of priming ejector dimensions were made.

Detail design of a priming ejector with integral air and shutoff valves was started in February, 1977 and completed in March.

A test rig was built in August, 1977 and the priming ejector was operated. Results of tests showed that the priming ejector was oversized and that its throat had to be reduced to achieve desired vacuum level.

Design modifications to the priming ejector were completed in September, 1977. The redesigned priming ejector was successfully tested in October, 1977. A vacuum equivalent to 20 ft suction lift was achieved in about a minute and a half with inlet conditions equivalent to compressor output with engine at idle.

Suction Pipe

Suction pipe requirements were established in October, 1976. Inlet bellmouth and screen dimensions were determined.

A vendor was selected in December, 1976 to design the suction system. The vendor completed stress and stability calculations and determined the structural design of suction pipe elements. It was decided that pipe elements were to be of fiberglass/foam construction. The design of pipe joints was completed.

Final dimensions of all suction pipe elements were determined in January, 1977. Inlet pipe section screen was redesigned for storing in the module.

In October, 1977, sample suction pipes were vacuum tested by the vendor with an NREC representative present. The test was successful.

In a suction and priming system test in January, 1978, vacuum grease was needed to keep some of the joints in the suction pipe sealed. This problem was solved by minor dimensional changes to the clamps and seals.

Check Valve

Design of the check valve was started in October, 1976 and was completed in December, 1977. Build of the check valve was vended out in January, 1978. The check valve was successfully tested in July, 1978.

Suction and Priming System Test

Suction and priming system operated satisfactorily in January, 1978 at a suction lift down to 11.5 ft. In May, 1978, the suction and priming system operated successfully at a suction lift of 20.5 ft.

Fuel and Lube System

Engine Oil System

The oil system design was started in August, 1976. An oil system flow diagram was prepared. Oil flow and heat rejection requirements for engine and pump were determined. A suitable off-the-shelf oil cooler and oil reservo . were selected. The location of oil cooler and duct work between oil coolers and ejectors were developed.

In October, 1976, a design layout was made to relocate stack ejectors, oil cooler, and ductwork to the top surface of the module above the engine.

Because of the possibility of seal failure in the pump, a separate pump oil system was designed to prevent sea water from entering the engine oil supply should such a failure occur.

In November, 1976, an improved oil cooler for the engine was disdovered. This heat exchanger (or cooler) is lighter in weight, thinner, and has a lower air-side pressure drop than the one previously selected. An oil reservoir/deaeration tank was designed for both oil systems.

Engine Cooling and Stack Design

In September, 1976, ambient temperature requirements for the engine were found and air flow requirements were estimated. A twin stack design with twin ejectors was selected.

Envelope cooling requirements were refined in November, 1976, and stack ejector size modified to correct air flow rate and pressure drop.

Fuel Tank

In September, 1976, capacity, dimensions, and other tank requirements were determined. The design concept for the structure of the tank and support of components to module base through the tank was developed. Materials were selected to stress requirements.

A support structure was designed in October, 1976 to carry engine/pump loads and to distribute these loads to the top of the fuel tank. A simplified construction concept for the tank was developed to reduce manufacturing costs.

In November, 1976, a low-cost tank structure was successfully devised with provisions for attaching module structure to the tank and internal routing of fuel lines. Detailed design of the tank was completed in December, 1976.

The fuel tank was assembled in October, 1977. Fuel pickup float valves assembled, tested, and installed inthe tank. A fuel level sensor and fuel delivery manifold were installed. The tank exterior was pa' ted.

Pump Oil System

In October, 1976, it was decided that two separate oil systems be used. Because of the possibility of seal failure in the pump, a separate oil system for the pump was designed to prevent sea water from entering the engine oil supply should such a failure occur. The pump oil system operates separately from the engine oil system.

An oil reservoir/deaeration tank was designed in November, 1976 for both oil systems.

Control System

Control Design

The design of the control system was started in June, 1976. Functional requirements of all parts of the control system were determined. A system schematic was prepared. Detailed wiring diagrams for various electronic subsystems were drawn up and components were specified. The control panel was designed and meters and indicator lights were selected.

Design of the control system was completed in July, 1976. The control system was functionally the same as described in the proposal, except if pump suction (prime) is lost during operation, the control throttles the engine back to idle and the priming sequence is restarted-- an amber light on the panel warns the operator of a NO prime condition. The proposed action had been to shut the engine down upon loss of prime. NREC felt this was undesirable in the event of temporary loss of prime, as might be caused by the maneuvering of the fireboat.

A meeting was held at NREC on August 10, 1976 for the purpose of reviewing the pump and other systems. Items discussed involving the control system only included:

1. Control schematic
2. Control panel layout
3. Shutdown parameters
4. Operating procedure
5. Explosion proof design

The design was found satisfactory. Some minor modifications recommended by NASA/Coast Guard personnel were incorporated into the design:

1. Rearrange red and amber lights for better grouping
2. Replace key switch with a toggle switch with a protective cover.

Another meeting was held at NREC on October 14, 1976 for the purpose of reviewing the design of the module. Representatives of NASA and the U. S. Coast Guard participated in the design review. Items discussed involving the control system only, included:

1. Any requirements imposed upon the control system by possible pump operation at zero flow shall be determined by NREC.
2. Potential effects of water hammer are to be taken into consideration when designing and controlling the system.

Control System Breadboarding

A breadboard control system was constructed, starting in October, 1976, for the purpose of evaluating the operation of the electronic portion of the controls.

Construction of the breadboard electronic control package was completed in December, 1976 and circuit checkout and box dimensions were determined.

Circuit checkout and debugging of electronic controls were completed in February, 1977.

Control Assembly

The control panel was assembled in November, 1976. In January, 1977

the water-pump lubrication system failure warning and shutdown interlocks were assembled and integrated into the control system.

In August,1977, mechanical components were assigned and prepared for testing. Assembly and wiring of control panel and electronic controls were completed. Mechanical control components underwent bench testing and development.

Development of the mechanical controls was completed in November, 1977. The mechanical controls were installed in the module. The wiring harness, electronic controller, relays, and solenoids were functionally tested.

The complete assembly of the controls and instruments was completed in December, 1977. All control components were installed and interconnected in preparation for functional checkout with engine and pump in the module.

Speed Controller

Several modifications to the pressure controller were tried on the module during the August, 1978, test series. None resulted in adequate operation. Meantime, a speed controller was designed as a backup. A speed controller is inherently simpler than a pressure controller. Having only one major component instead of two. Parts for the speed controller were fabricated for trial on the module in September.

The change to the speed control was approved by NASA and USCG personnel in September, 1978. A prototype was built and assembled.

The first speed controller was too sluggish in shutting the engine down. Major design changes were made in October, 1978, on the speed controller which included redesigning the hydraulic actuator. Bench tests proved successful.

The development of the speed controller and hydraulic actuator was completed in December, 1978.

During the Acceptance Test in January, 1979, oil leakage was observed from the hydraulic actuator. A new preformed packing was installed to stop the leak.

Battery Test Circuit

The battery test circuit as originally designed was inadequate. A

revised circuit was designed in August, 1978, and was made ready for September testing in breadboard form.

The design of the battery test circuit was completed in September, 1978. Tests of the breadboard circuit in November, 1978, by a vendor revealed some stability problems. Design modifications were made.

In December, 1978, the battery test circuit was complete. It was installed and tested satisfactorily in the module.

Module

Support System

In August, 1976, the design of a mounting system to control shock loading on the engine and pump from a 1 ft drop requirement began.

Engine shock requirements were established in September, 1976, to meet load limits and vibration isolation. A design concept for interface between shock mounts and module structure was developed.

Shock mounts for the engine were selected in October, 1976. A support structure was designed to carry the engine/pump loads and to distribute these loads to the top of the fuel tank.

The mount structure at the engine/pump interface was redesigned to compensate for differential thermal expansion between the engine and the pump while maintaining alignment of the quill shaft.

Module Structure Design

The engineering design of the structure was started in August, 1976. Effects of loads imposed on the structure by helicopter or forklift truck lifting; by a 1 ft vertical drop, and by gusts of wind to 100 mph were evaluated and the structure was designed to withstand these loads.

A preliminary layout of the module was completed in September, 1976. All module components, including fire-fighting equipment components were included in the layout.

In October, 1976, the module layout and packaging design were refined. Trade-offs among various methods and materials of construction were

evaluated for their influence on weight, structural integrity, and cost. The size, location and construction of doors was investigated.

A fiberglass foam-sandwich construction material was selected in November, 1976, for the module skin structure. A vendor was chosen to prepare construction details.

Detailed design of the module structure was completed in March, 1977.

Module Design Review

A meeting was held at NREC on October, 14, 1976, for the purpose of reviewing the design of the module and the various subsystems. Representatives of NASA and the U. S. Coast Guard participated in the design review. Items discussed, involving the module system design only included:

1. Holes in Fuel-tank baffles must not be too small
2. G-loading on the module at helicopter liftoff to be checked with Sikorsky.
3. The top of the module must be strong enough to support personnel.
4. The battery must be placed in a leakproof container and vented overboard.
5. The filler port must be located outside the module skin and far from the battery and electrical system.
6. The exhaust stack air ejector must provide sufficient flow capacity to take care of engine skin heat load.
7. Doors not to exceed 18 inches in width, should be hinged to swing horizontally, and have a minimum number of latches. The number of doors should be minimized by combining functions.

A refined packaging layout was discussed in December, 1977 with representatives and the U. S. Coast Guard. Changes agreed upon were incorporated into the packaging layout.

Module Assembly

The assembly of the module began in September, 1977. Structural parts were assembled on October, 1977, fire wall and various plumbing were installed in the module. The fuel tank was installed.

In November, 1977, insulation, plumbing, instrumentation, wiring harness, and mechanical controls were installed in the module. The dolly was received.

The module structure assembly was completed in December, 1977. All control components were installed in the module. Pump Build No. 4 was installed in the module and interconnections were made. The assembly of the module was completed in January, 1978.

Fire-Fighting Equipment

During the module design review in October, 1976, NREC suggested that current stainless steel monitors be replaced by a lighter weight aluminum or fiberglass construction.

Starting in January, 1977, samples of monitors, Storz couplings, hose, and fire suits were obtained. Evaluations were made for suitability of equipment, dimensions, and storage requirements. A vendor was selected to build fiberglass monitors.

The fiberglass monitor went through a long development process by the vendor. Tooling and molds had to be built. Finally in July of 1978, the first fiberglass monitor was received. It was tested during the August, 1978, endurance test. There were a few minor modifications required, so the monitor was sent back to the vendor. Permission was given to start building the second monitor.

The first monitor was tested in December, 1978, and January, 1979. Some problems with excessive leakage and base strength were found. The base was strengthened and was successfully tested to twice design stress. The second monitor was completed and both monitors were successfully tested to 450 psi. At the end of April, the monitors were complete except for minor cosmetic work. The monitors were delivered to the Coast Guard in May, 1979.

TESTING

In this section of the report the test records and procedures are recorded chronologically. The tests are broken down into four sub-sections dealing with pump tests (builds 1 to 5) run at NREC, component tests, field tests at other locations, and U. S. Coast Guard tests at Mobile, Alabama.

Pump Tests in Laboratory (Builds 1 to 5)

Initial Preparations

Test cell preparations were started in December, 1976 and a pump test plan was written. It was decided that initial testing would be done at NREC. A module was obtained from Aviation Power Supply that contained an engine control and lubrication system and could easily accept the NREC pump and an Allison engine. Design work began on a closed water test loop.

In January, 1977, the Allison engine was installed in the APS module. It was placed on existing mounts and hook-up were made. The pump was installed on custom mounts and quill shaft connection was made to the engine as shown in Figure 18.

The closed-loop water test rig was assembled in January, 1977 and was completed in early February. See Figure 19 for drawing of test loop.

Instrumentation

Connections were made to pump sensing devices as shown in Figure 20 to monitor pump operation. These instruments and transducers on the test rig were:

- Torque Meter Pressure Readout
- Speed Pickup (Pump)
- Speed Digital Readout
- Flow Meters, Turbine type -2
- Pressure Taps (static):
    - Inducer Inlet - 4 interconnected
    - Inducer Discharge - 3 separate
    - Pump Inlet - 4 separate

Pump Throat - 2 separate

Volute Periphery - 4 separate

Volute Discharge - 4 interconnected (1 diam. downstream)

Pressure Readout

Vibration Pickup - Engine

Vibration Pickup - Pump

Temperature - Inlet

Temperature - Discharge

Pressure Pulsations at Pump Throat and Discharge - Display (Scope) 2 Transducers

All test instruments were calibrated prior to testing. Instruments all met the following accuracies:

Flow Rate: $\pm$ ¼% of point

Pressure: $\pm$ ¼% of point

Torque: $\pm$ ¼% of point

Pressure Sensor:

Speed: $\pm$ 10 rpm, 300 - 6315 rpm

Temperature: $\pm$ 1°F, 50 - 300°F

Pump Test 1/Build No. 1

Pump testing was started in February, 1977. The pump, inducer, and assembly tests were combined into a single assembly test series, with interstage instrumentation to provide information on component performance. During February three tests were run, one with air and two with water. The air test demonstrated the ability of the pump and engine to run at speeds up to 5000 rpm with no mechanical difficulties. The two water flow tests were run at half speed only, because of torque limitations on the inducer impeller. Sufficient test data was obtained to define a limited portion of the head-flow characteristic at half speed (3150 rpm) and atmospheric-pressure inlet (Fig 21). These initial runs served also to debug the newly-installed water-flow loop; a number of problems with valves, flowmeter, and leakage were discovered and have been corrected.

Pump Test No. 2/ Build No. 1

Pump testing was continued in March. Several test runs were made early in the month and data were taken at 3150, 4500, and 6315 rpm. These data are plotted in Figure 22 for comparison with the design pump performance. Because of a flange failure in the water test loop, only one data point was obtained at full speed (6315 rpm). The data indicate that the pump flow rate is about 15 per cent short of the design goal. From detailed analysis of the static pressures at various locations in the pump it has been concluded that the NPSH requirement of the main impeller is not being met.

The pump ran at full speed for about 10 minutes before the test loop failure. Subsequently, the pump and test loop were disassembled to make various modifications aimed at improving the performance of the pump and of the test loop. The pump modifications are as follows:

1. Cracks between the trailing edges of the inducer stator vanes and shroud were filled, to eliminate any leakage.
2. The leading edges fo the main impeller blades were filed on the suction side, to improve the inlet incidence angle.
3. The clearance at the main impeller shroud was reduced to 0.010 in (design value).

Test loop modifications are as follow:

1. Instrumentation of the pump was improved by replacing some slow-response pressure lines with larger-diameter tubing, and by adding two static taps and a high-speed piezoelectric pressure transducer at intermediate points in the inducer.
2. A swirl-type air separator was installed in the water loop to aid in the reduction of air content in the water.

These modifications were nearing completion by the end of March.

Pump Test 2/Build No. 2

Pump testing was continued in April. The modification to the pump and test rig described above were completed. Tests of the modified pump were run on April 15, 19, and 20. Data was recorded at various speeds between 4500 and 5600 rpm. These data have been scaled to the design speed

of 6315 rpm and are plotted in Figure 23. The design head-flow and efficiency curves are also plotted. Comparison shows that at the design flow rate of 2200 gpm the pump is within a few per cent of its design goal.

A systematic error in the flow measurement was discovered and corrected early in the April test series. The pulse rate outputs of the magnetic pickups on the turbine flowmeters are read by digital counters. One of these counters was found to give a consistently low reading when connected to one of the magnetic pickups; low, that is, in comparison to the reading on two other counters connected to the same magnetic pickup. It was found that the threshold voltage required to trigger this counter was too high for the relatively weak signal put out by the magnetic pickup. Accordingly, this counter was switched to a less sensitive duty and a more sensitive counter substituted.

Because the malfunctioning counter was used in obtaining test data published in the March progress report, it is not possible to determine whether or not the substantial improvement in flow measured in the April tests is due in part to the modifications made to the pump in the interim. It is clear, however, that there was a substantial improvement in head rise from the March to the April tests, and it can be inferred that the flow rate improved also.

The attempts to remove air bubbles from the rig were of only limited success, and all the data taken so far are for water containing numerous tiny air bubbles. The volume fraction of air contained in these bubbles is estimated to be of the order of one to two per cent. The presence of bubbles has an adverse effect on NPSH and tends to make a pump cavitate at a flow rate lower than it would in the absence of air. Accordingly, the pump performance would be expected to improve if it were supplied with water containing less air.

On April 20 a pump failure occurred. Upon disassembly of the pump it was found that the main pump shaft had been misassembled and that the pump had been run for about 10 hrs of testing with inadequate control over the axial position of the main impeller. Wear caused by net unbalanced axial thrust (normally absorbed by the ball bearings) finally led to the failure.

At the end of April the flowmeters were removed from the water loop. Arrangements were made to take the flowmeters to the Alden Hydraulic Laboratory in Holden, Massachusetts for calibration early in May.

A new set of test parts with several modifications to the hydraulic flow path was machined. These modifications included:

1. Thinning and extension of the blades on the inducer impeller. This will produce an increase in head and smaller wakes at the impeller discharge.
2. Casting of the inducer housing in one piece. This will produce smoother interstage diffuser passages with less blockage and tendency to flow separation.
3. Increasing the shroud diameter at the inlet to the main impeller. This will reduce the NPSH requirement of the main impeller.
4. Increasing the backslope of the main impeller. This will increase the discharge pressure and make the head-flow characteristic generally steeper.

The above changes together are expected to result in a pump performance that will meet or exceed the design curve shown in Figure 23. Parts for this improved version of the pump will be ready for test in mid-May.

Pump Test 3/Build No. 3

Pump testing was continued in July. The pump was put on test in mid-month and performance data was obtained at 5500 and 6300 rpm (full design speed). Pump performance was slightly lower in head than that measured in the series of tests carried out in April. This was attributed to excessive shroud clearance in the main pump, caused by machining errors. Suction lift was satisfactory. The pump operation was demonstrated for NASA and Coast Guard representatives on July 26 and 27.

Pump Test 4 and 5/Builds No. 4 and 5

In early September two pumps were assembled and tested. The test data for these two pumps are shown in Figures 24 and 25. While both pumps fall short of the performance goal of 408 ft of head rise at 2200 gpm, each exceeds the original Coast Guard specification of 150 psi at the monitor at

1500 gpm. Pump Number 4 was subsequently installed in the Coast Guard module. After the engine has been equipped with high-speed gears, the pump will be operated at 6600 rpm instead of the current 6315 rpm. This speed increase will result in higher head rise at increased flow rate.

Test data taken on September 8, 1977 and witnessed by NASA representatives demonstrate the capability of the pump to operate at equivalent suction lifts exceeding 20 ft.

Module Functional Tests

Control Checkout Tests

These tests were started in December, 1977. The module was operated on both freshwater and sea water. The pump was tested at full speed (6600 rpm) with various nozzles used. The data obtained in these tests is given in Table I. All module systems were checked out and found to operate properly with the exception of the following:

1. Turbine Exhaust Temperature Shutdown. This circuit required the addition of a time delay to prevent tripping on engine starting transient.
2. Priming Circuit Float Switch. The float switch was replaced by a pressure switch activated by pump discharge because air was being trapped in the float switch cavity.
3. Fuel Shutoff Valve. A replacement fuel shutoff valve was procured because the previous valve, when de-energized, did not shut off the fuel supply.
4. Water Pressure Controller and Hydraulic Activator. The hydraulic water pressure controller and engine hydraulic actuator were redesigned to respond properly to control lever position.

In February, 1978, control system modifications with the exception of the pressure switch were made and the module was reassembled. Functional checkouts were made concurrently with endurance testing. Control system problems encountered and corrective action was as follows:

1. The turbine exhaust temperature circuit in the electronic controller as designed did not permit short-duration over-temperature

transients as required by the engine for startup and acceleration. A delay was built into the circuit. This modification was bench tested and installed on the module and retested.

2. The pressure switch replacing the float switch in the priming circuit was not received for this test.
3. The fuel solenoid shutoff valve did not close properly. A new valve was procured.
4. The pressure controller and engine governor actuator required some modification to improve starting and response to changes in the control lever. The actuator was modified, tested on the module and found acceptable. The pressure controller required a minor change to adjust the gain and prevent hunting.
5. The speed circuits in the electronic controller were found to be sensitive to humidity and to the signal level produced by the speed sensors. The humidity sensitivity was eliminated by conformal coating of the circuit boards after all circuits are operating satisfactorily. The signal level problem was solved by a design change to the speed circuits. A new hard wired speed circuit board was built and tested on the bench. This circuit accepted input signals a factor of ten lower than the previous circuit and was not sensitive to component specification variation (within manufacturers tolerance). This circuit was installed on the module and retested.

Low Suction Test

In January, 1978, the module was tested at suction lifts down to 11.5 ft. The average time to prime the pump was less than one minute. The pump was operated at full speed with pressure and flow at normal expected operating conditions (see Table I).

High Suction Test

The high suction test was started in February, 1978. In the course of functional and endurance testing, the pump was primed and operated at lifts up to 19 ft. The primer primed the pump in 1-1/4 mins at 19 ft and the pump

operated successfully at this suction lift. In May, 1978, the pump was primed successfully to 20.5 ft.

Field Tests

Endurance Tests

An endurance test program was started on February 6, 1978. The module was transported to Munro Drydock in Chelsea, Massachusetts. The first segment of testing ran until February 27 in which 45 hrs of running time had been accumulated on the module. The data from a typical endurance test is shown in Table II.

In the earlier part of the first segment of endurance testing, a small pinhole leak developed in the volute that slowed down the operation drastically. The endurance test was terminated in February because of pump leakage, performance degradation, and suspected main impeller blade failure. Upon disassembly it was discovered that the main impeller had lost a 2 in segment of one blade tip through fatigue fracture (see Fig 13).

The second segment of endurance testing started in May, 1978. The pump was modified to correct problems encountered in the previous endurance test series. Eight additional hours were accumulated before a pump shaft failure occurred on June 6.

The problems encountered in the second segment were corrected and the module was reassembled. The third and final segment of endurance testing started in August, 1978, and ran until September 12, when an inducer blade failure caused testing to be suspended. Thirteen hours of running time were accumulated on the module during this third segment, which brought the total module hours to 75.

Performance Tests

Performance testing of the pump in the module was carried out in May and June, 1978. The performance tests included calibration of the Stang nozzle flow measurements against volumetric measurements in a tank. The performance data is summarized in Figure 26; all speeds have been scaled to 6315 rpm for direct comparison with previous data.

The scaled data indicates that at 6315 rpm the pump head rise and flow rate comfortably exceed the design goals of 408 ft at 2200 gpm. The pump efficiency peaks at about 74 per cent. This is below the original estimate of 85 per cent, but above the approximately 70 per cent efficiency of the pump as tested in the module in February.

It is of interest to compare the performance of the pump with the power available from the engine. Engine power is strongly affected by ambient temperature, dropping from 346 hp at 60 deg F to 325 hp at 80 deg F to 300 hp at 100 deg F. Figure 27 shows the approximate performance limits imposed on the pump by the engine at these three ambient temperatures. On a 100-degree day the flow rate at 150 psi nozzle pressure will be limited to about 1700 gpm. This limitation is, of course, directly related to pump efficiency. If the pump were 85 per cent efficient (as designed) the engine power would be sufficient to meet design performance even on a 100-degree day.

On November 14, 1978, a 2.6 hr performance test was run as a shakedown of module to test the operation of the low speed gears that were just installed in the pump.

Module Inspection, Demonstration, and Acceptance Test

The module was inspected by NASA and USCG representatives on December 7, 8, and 11, 1978. An official operating demonstration was held for government representatives on December 12. Because of deficiencies in the operation of the control and charging system, acceptance was postponed. On January 12, 1979, a second inspection by NASA and USCG representatives was held, and the module was officially accepted by NASA and was delivered to the Coast Guard.

Official Acceptance Test

The Official Acceptance Test of the U. S. Coast Guard Firefighting Module was performed in Cambridge and Boston, Massachusetts, by NREC personnel and witnessed by representatives of NASA and USCG. Parts of the Acceptance Test were carried out on December 8 and 11, 1978; the remainder was completed on January 12, 1979. Completion of the Acceptance Test was

an important milestone in the development of the module; it was followed immediately by formal transfer of the module from NREC to the U. S. Coast Guard.

The Acceptance Test Procedure is described in Appendix A. This procedure was followed, with the following exceptions.

1. Acoustic noise level was not measured.
2. One-sided performance was not tested.
3. Lift was limited to 18.5 ft.

Pump performance during the Acceptance Test is documented in Figure 28. Data sheets containing the data recorded during the Acceptance Test are shown in Appendix B.

Problems and Correction Action (Module)

Several problems were encountered during operation of the module in the December tests. These problems and corrective action taken are as follows:

1. Overspeed shutdown at 6,600 rpm. The calibration of the overspeed circuit was found to be in error. The set point was recalibrated to shut down at 6900 rpm (105 per cent power turbine speed) as designed.
2. Failure of the starter-generator to charge the batteries. The regulator set point was recalibrated to prevent premature tripping of the circuit breaker.
3. Intermittent failure of the engine starting sequence. This problem was traced to a broken connection in the main connector of the wiring harness. This connection was repaired.
4. Oil leakage from the hydraulic actuator. A new O-ring seal was installed to stop the leak.

In addition to the above problems, it was observed that the wiring harness and connections had been the cause of a number of module operational failures. To increase the reliability of the wiring, a systematic inspection and upgrading of the wiring was carried out. Several troublesome connectors were replaced. All individual wires were bundled and wrapped. Connector pin-wire joints were inspected and repaired where necessary.

Support of wires and connectors was improved, and wire bundles were moved from locations where they might be vulnerable to oil or water contamination.

Upon completion of the previously mentioned steps and prior to the continuation of the Module Acceptance Test in January, the module was tested by NREC. Repeated starts and stops demonstrated a high degree of reliability.

Problems and Corrective Action (Fiberglass Monitors)

During the December tests the fiberglass monitors were found to have two problems:

1. Inadequate base strength. One monitor base broke during a test.
2. Excessive leakage at joints.

The base thickness and strength were greatly increased, and tests were run in the laboratory at forces up to four times those found in service. Improved O-ring seals were installed to reduce the leakage.

The monitors were retested in January at full module flow. Two problems were found:

1. Leakage at the joints confirmed to be excessive.
2. Articulation of the monitors was loose at low pressure and tight at high pressure.

The monitors were retained by NREC for pressure testing and improvement of the seals. Upon completion they were delivered to the Coast Guard.

U. S. Coast Guard Tests (Mobile, Alabama)

Test Summary

Upon acceptance in January, 1979, the module was shipped to the Coast Guard test facility in Mobile, Alabama for field testing. An endurance test of 100 hrs was run with the module mounted on a barge and, subsequently, on the dock. During this period the pump, engine, and other major mechanical components operated without problems. Some problems were encountered with the electrical system and with the fuel system; these were successfully overcome by the joint action of NASA, USCG, and NREC personnel. These were as follows:

1. After 50 hrs of operation in very rainy and humid weather, it was found that the relay box had become water damaged. A new relay box was installed. Sealing of the relay box and drainage of

water from the module were improved to prevent recurrence.

2. After 88 hrs the starter-generator voltage regulator ceased to function and had to be replaced with a spare.
3. After 88 hrs the connector pins for the thermocouple (turbine temperature) input at the electronic module failed and were replaced.
4. After 88 hrs the solenoid operator on the fuel bypass valve failed and had to be replaced. (This failure occurred again after 130 hrs.)

After completion of the 100-hr endurance test, the test program was continued. Various operational tests were performed, including operation from a 32-ft patrol boat, helicopter lifting, and a 1-ft drop test. As of the end of April, the module had accumulated about 130 hrs of operating time.

Pump Disassembly, Inspection and Rebuild

After approximately 130 hrs of endurance and operational testing in June, 1979, the fire fighting pump was removed from the module for teardown, inspection, and refurbishing. The inspection results are described in Appendix C.

CONCLUSIONS

A prototype fire-fighting module has been designed, built, tested and delivered to the U. S. Coast Guard. The characteristics and performance of this module meet the contract specifications. More important, the original intent and spirit of this development program have been fulfilled, namely, to create a portable fire-fighting unit of high pumping capacity that can be rapidly deployed in a wide variety of ways to fight fires on shipboard and ashore. The many uses of this high performance unit are expected to become more and more apparent as experience with it in actual fire-fighting accumulates.

TABLES

TABLE I

TEST DATA -
MODULE FUNCTIONAL CHECKOUT AND LOW SUCTION TESTS

Date (1978)	1/18	1/27	1/27	1/27
Run No.	1	1	2	3
Salt or Fresh Water	Fresh	Salt	Salt	Salt
Water Temperature*, deg F	$\sim$32	$\sim$32	$\sim$32	$\sim$32
Suction Lift, ft	8.5	11.5	10	10
Pump Inlet Static Pressure, psia	11	--	--	--
Pump Discharge Static Pressure, psig	115	153.5	186	142
Nozzle Inlet Total Pressure, Right, psig	95	125	156	106
Nozzle Inlet Total Pressure, Left, psig	95	129	159	110
Nozzle Tip Diameter, in	1 3/4	1 3/4	1 5/8	2
Pump Speed, RPM	5500	6280	6680	6570
Gasifier Speed, per cent	103	100	98.5	98.5
Engine Torgue Pressure, psig	50.5	65.2	72.2	72.0
Inlet (Ambient) Air Temperature*, deg F	$\sim$32	$\sim$30	$\sim$30	$\sim$30
Turbine Temperature, deg F	1123	--	--	--
Engine Oil Pressure, psig	124	125	123	125
Pump Oil Pressure, psig	110	112	112	112
Engine Power, hp	175	259	302	297
Water Flow Rate**, gpm	1800	2100	2000	2500

* Not recorded, estimated.

**Flow rates are estimated from nozzle pressures.
Rates may be inaccurate.

TABLE II

TYPICAL ENDURANCE TEST DATA

Test: Endurance Date: February 20, 1978

Equipment

Monitors: 2 - 3" Stang Nozzles: 2 -1-5/8 diameter

Hose: 2 - 25' x 4" diameter Valves: 2 at module

	Run Number					
Independent Instruments	9	9	9	9	9	9
Gasifier Speed, Hz	284	284	284	312	312	315
Pump Speed, RPM	6550	6580	6560	6110	6100	5980
Pump Inlet Pressure, psia	9.0	8.5	8.1	9.7	10.0	11.5
Pump Discharge Pressure, psig	183	183	181	177	175	175
Nozzle Inlet Pressure, psig, Right	158	160	160	82	80	40
Nozzle Inlet Pressure, psig, Left	156	156	156	78	80	42
Engine Torque Pressure, psig	70.6	70.6	70.0	58	57.8	49.8
Water Lift, ft	14	16.5	17.5	18	17.5	17
Water Temperature, deg F	35	--	--	37	37	--
Air Temperature, deg F	27	34	35	34	31	31
Barometric Pressure, in Hg	30.1	--	--	--	--	--
Engine Vibration, y, in 2	~0	~0	~0	~0	~0	~0
Pump Vibration, Inlet, in 3	5-15	5-15	5-15	5-20	5-20	5-20
Turbine Temperature, deg F	1360	1340	1368	1194	1209	1186
Engine Oil Temp, deg F	180	177	182	159	154	171
Time to Prime, sec	45	--	--	45	45	--
Valve Position, Left, deg	0	0	0	55	55	75
Valve Position, Right, deg	0	0	0	50	50	70

TABLE II (CONTINUED)

TYPICAL ENDURANCE TEST DATA

	Run Number					
Panel Instruments	9	9	9	9	9	9
Engine Oil Pressure, psig	122	126	125	126	126	125
Pump Oil Pressure, psig	109	111	111	110	110	109
Pump Inlet Pressure, in Hg	9.5	9.0	12.0	7.5	6.0	0
Pump Discharge Pressure, psig	182	188	180	177	176	177
Control Lever Position	Run	Run	Run	Run	Run	Run
Turbine Temperature, deg F	--	--	--	--	--	--
Pump Speed, RPM	6620	6640	6620	6100	6080	5900
Battery Current, amp	10	0	0	32	0	0
Indicator Lights On	None	None	None	None	None	None
Hourmeter	80.1	81.1	82.1	82.3	83.1	83.3
Time and Fuel						
Time of Reading	1304	1353	1454	1559	1700	1710
Time Start-Stop	Start 1255		Stop* 1456.	Start** 1555	Start 1656	Stop 1714
Accumulated Time	23:59		26:00			27:00
Fuel Added, gal	33				75	

Comments

* Shutdown at 1456 due to high EGT, rinsed engine with pure water before restarting for final hour.

**Shutdown 1637 for low fuel.

FIGURES

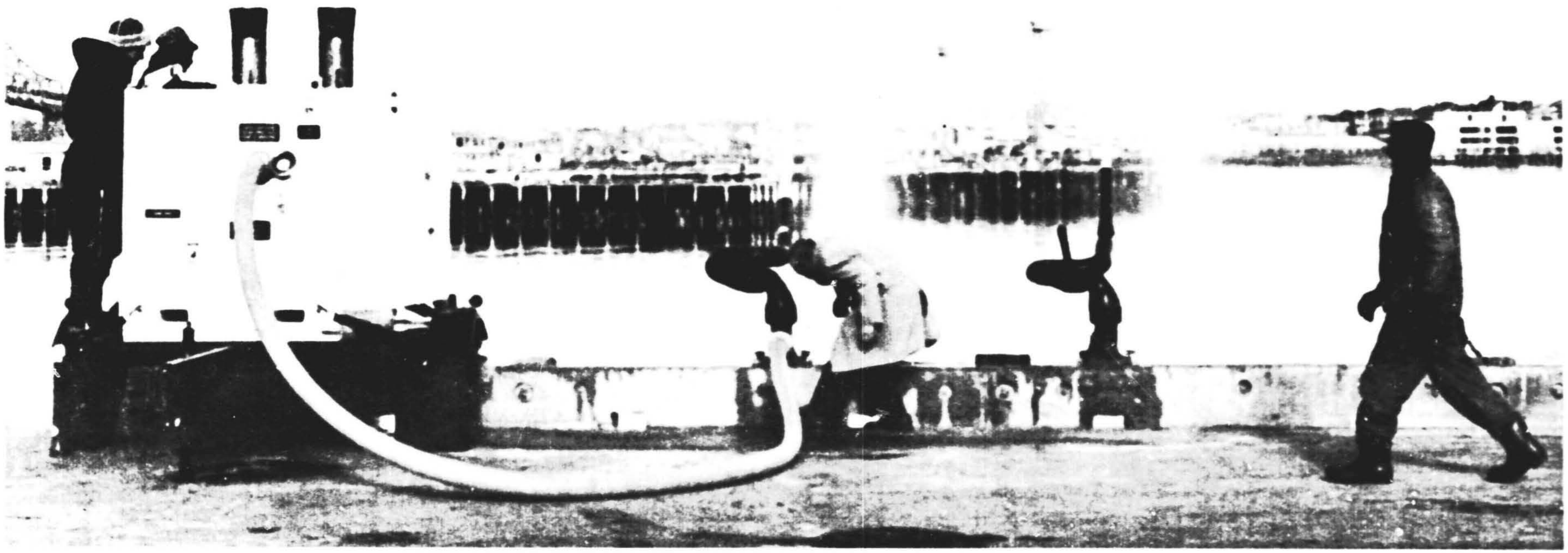


FIGURE 1 - FIREFIGHTING MODULE IN OPERATION

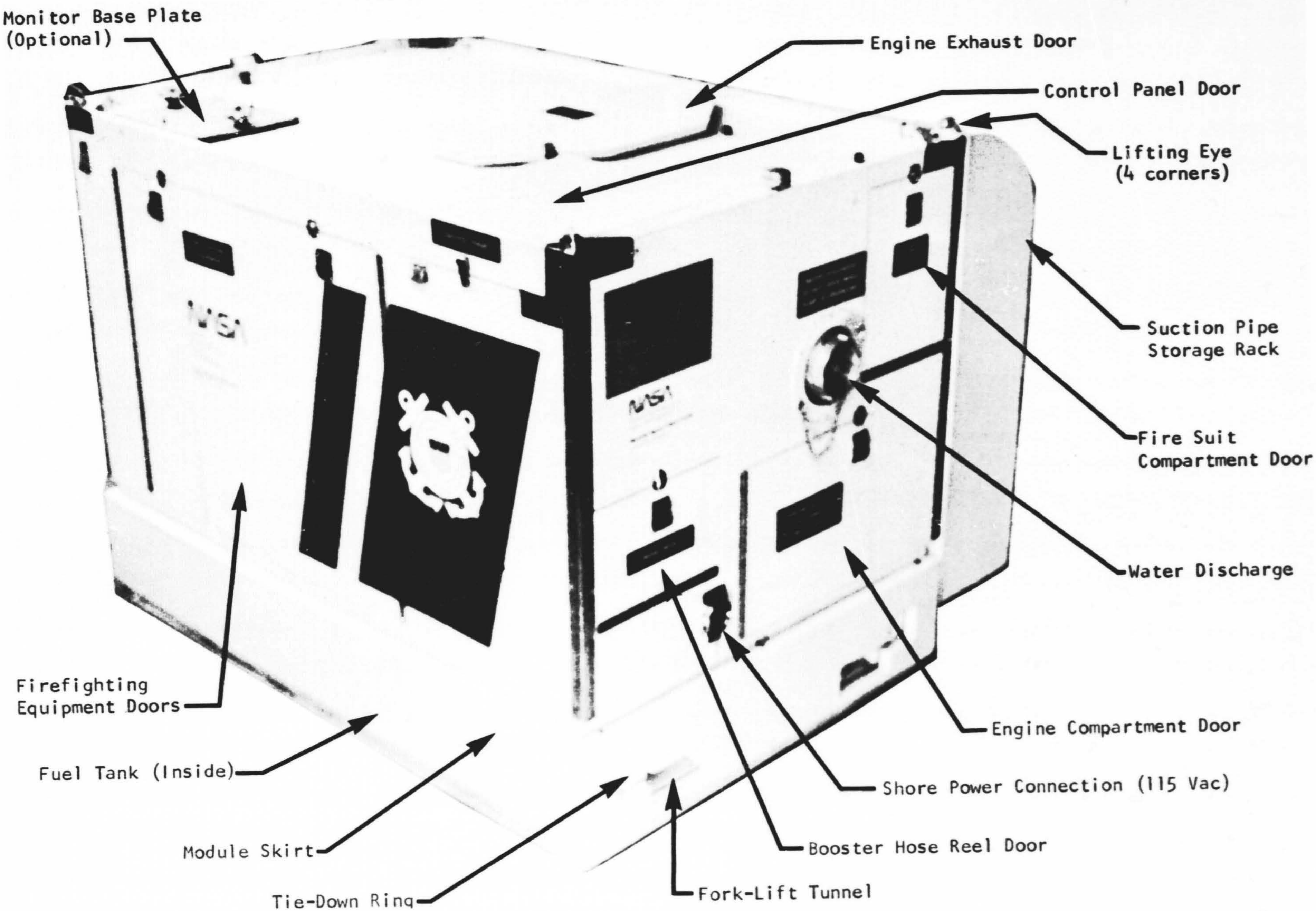


FIGURE 2 - FRONT VIEW OF MODULE WITH ALL DOORS CLOSED

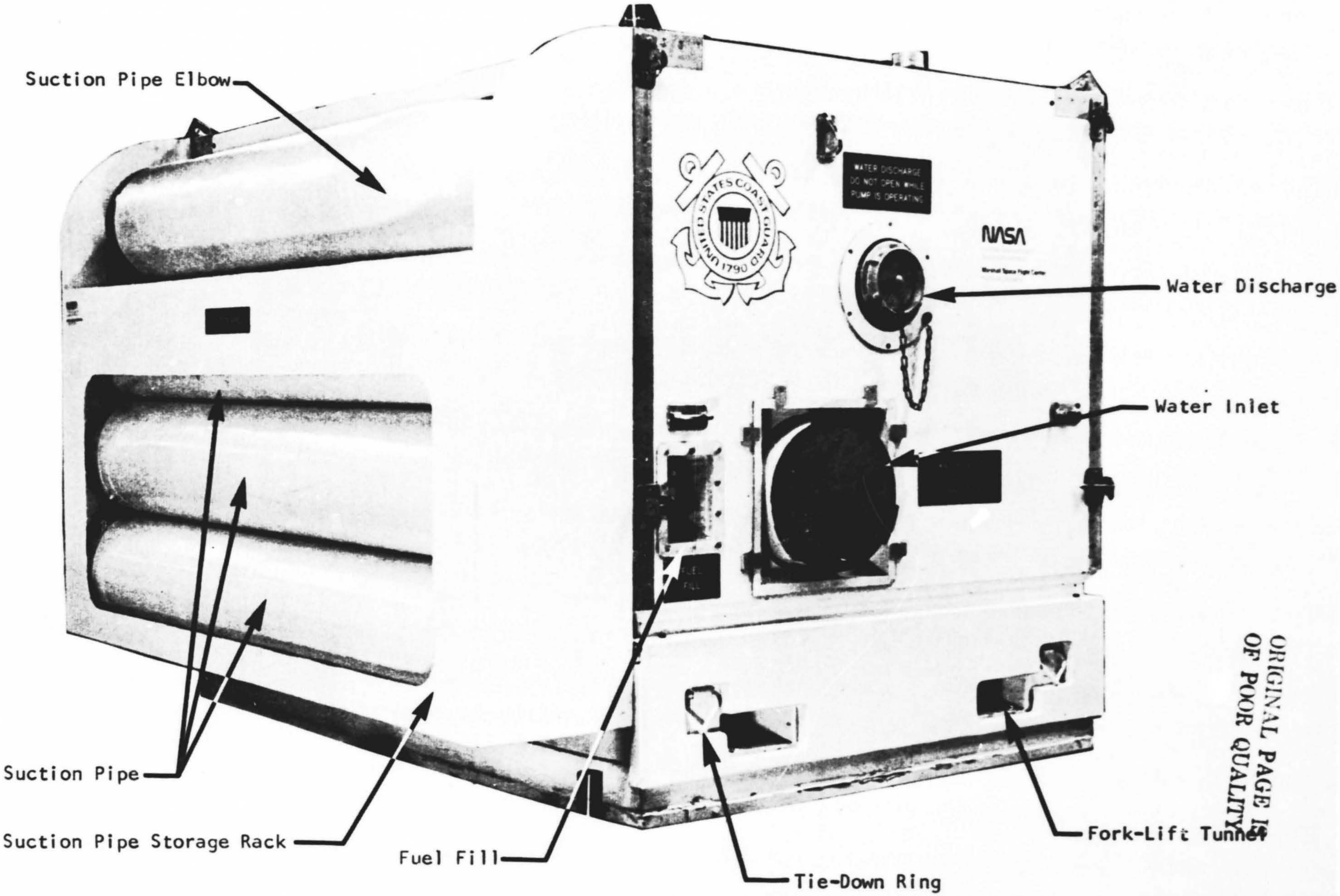


FIGURE 3 - REAR VIEW OF MODULE

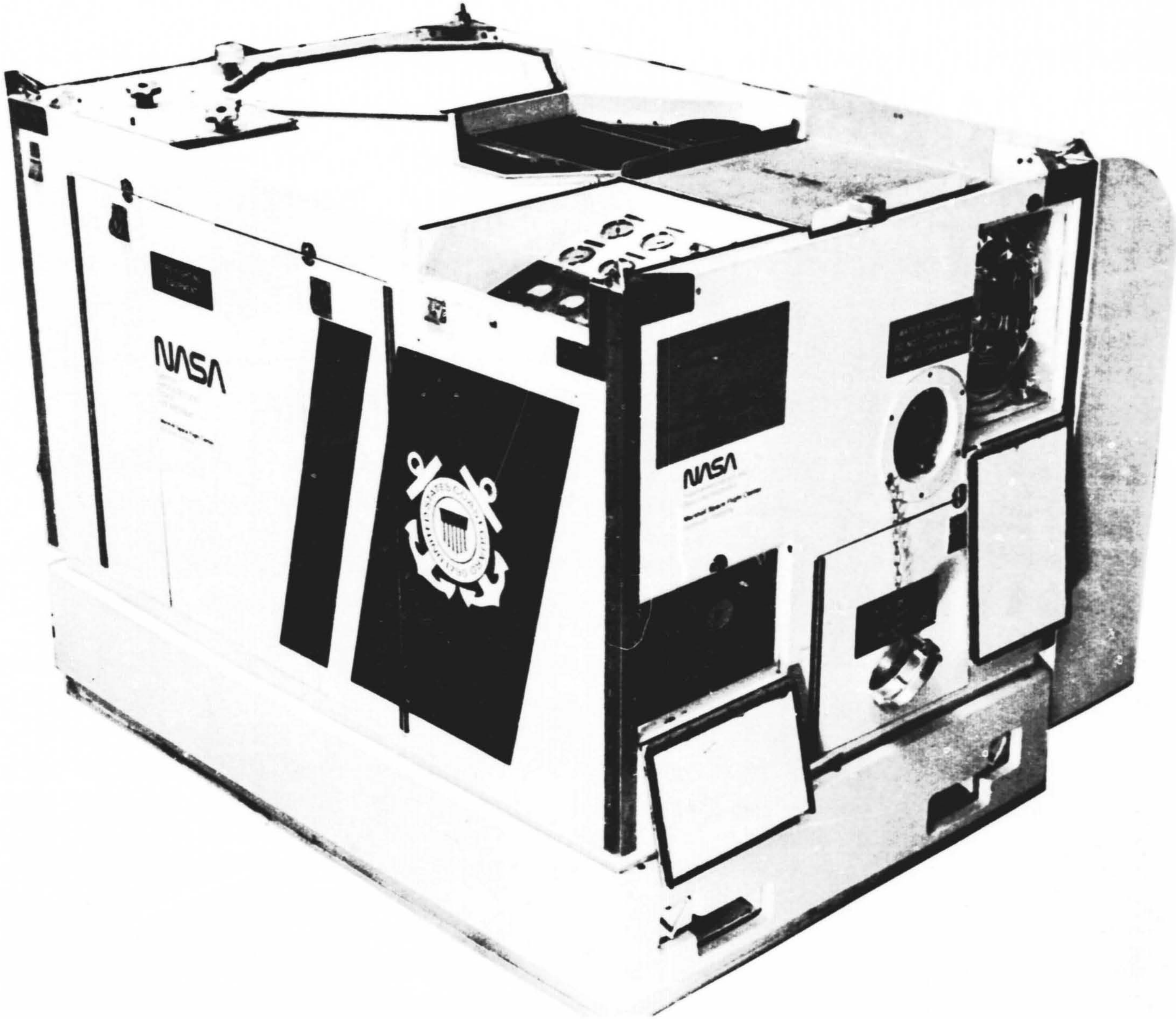


FIGURE 4 - FRONT VIEW OF MODULE WITH TOP DOORS AND EQUIPMENT ACCESS DOORS OPEN

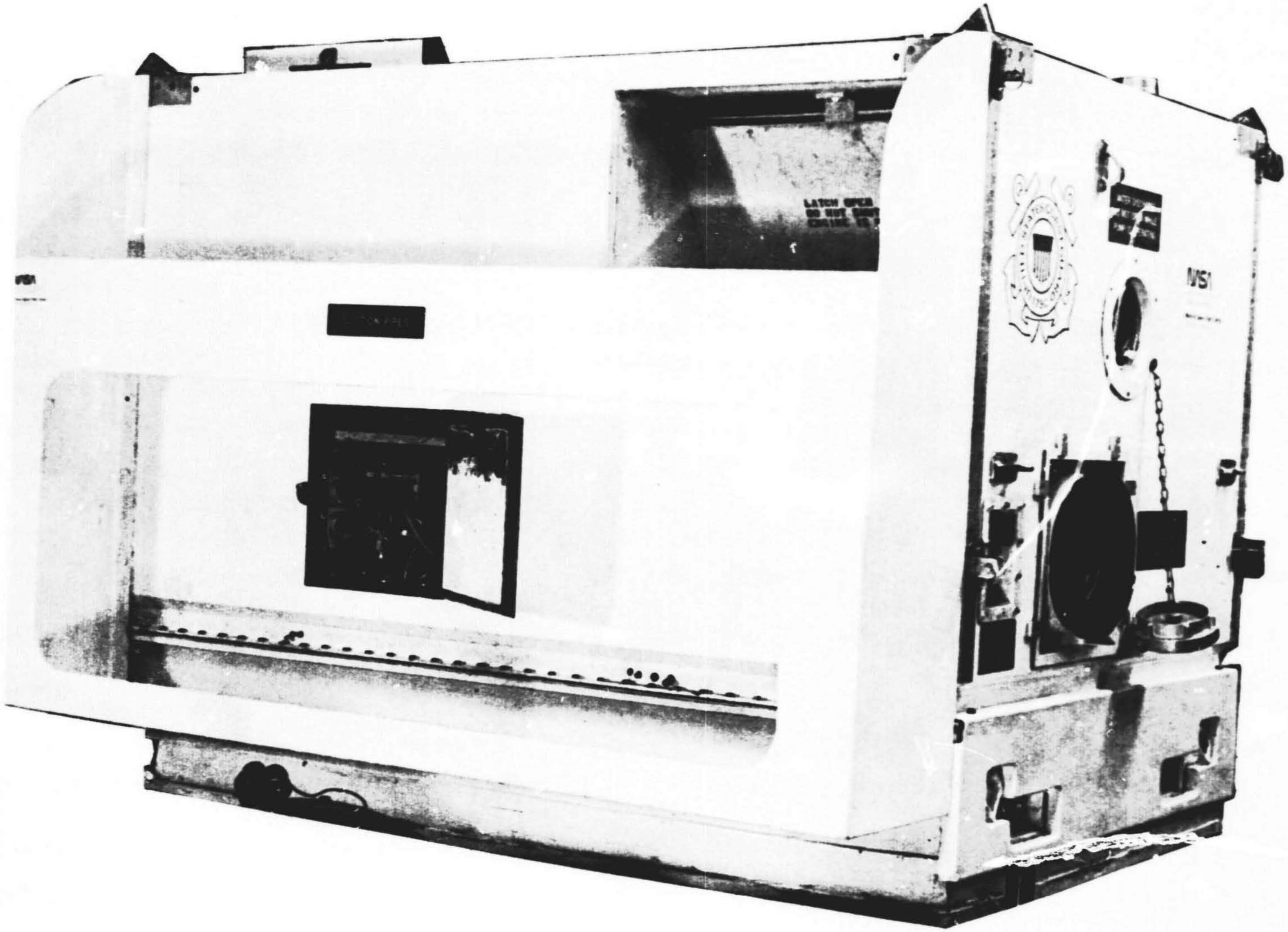


FIGURE 5 - REAR VIEW OF MODULE WITH SUCTION PIPES REMOVED AND INLET AND DISCHARGE UNCOVERED

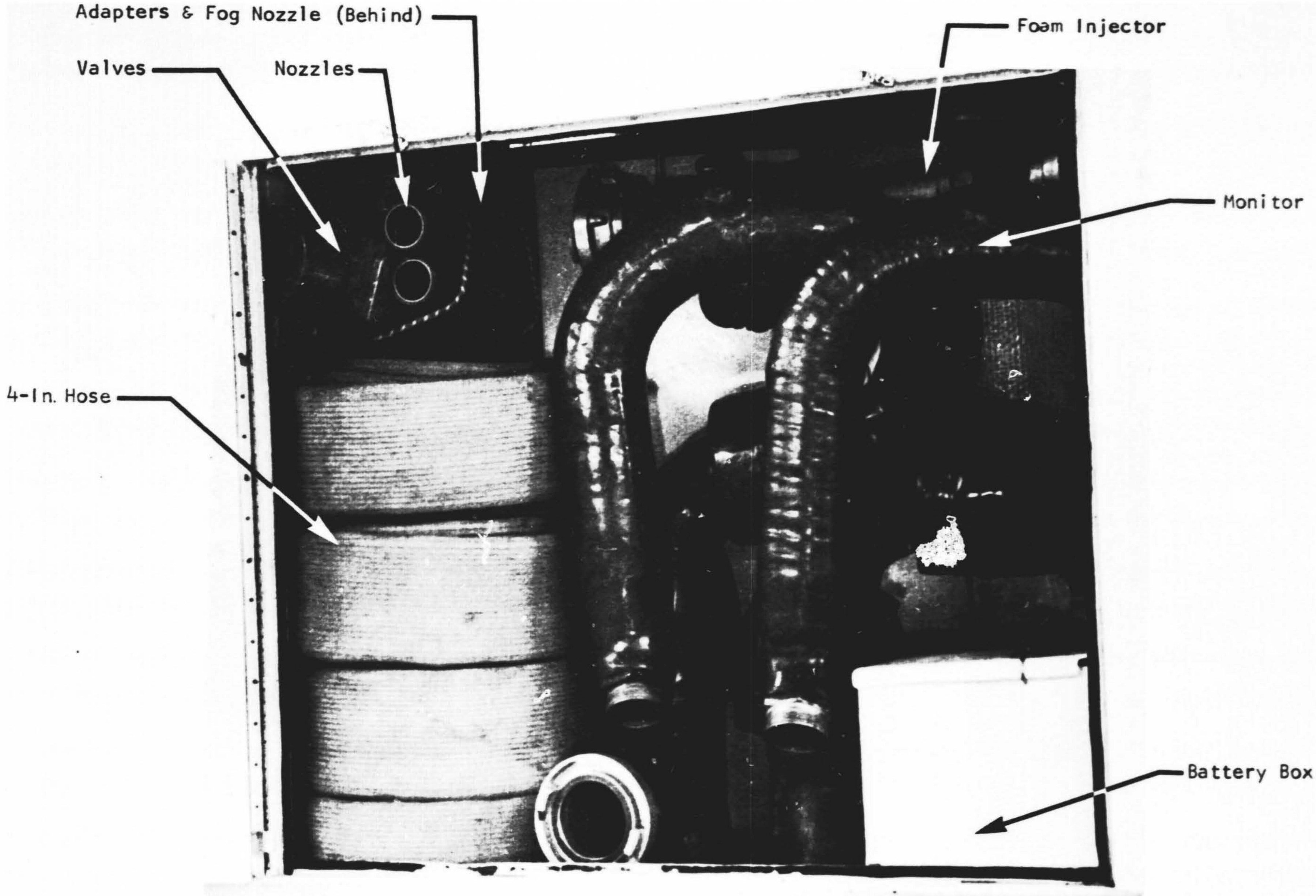


FIGURE 6 - STORAGE OF FIRE-FIGHTING EQUIPMENT
IN MODULE FRONT COMPARTMENT

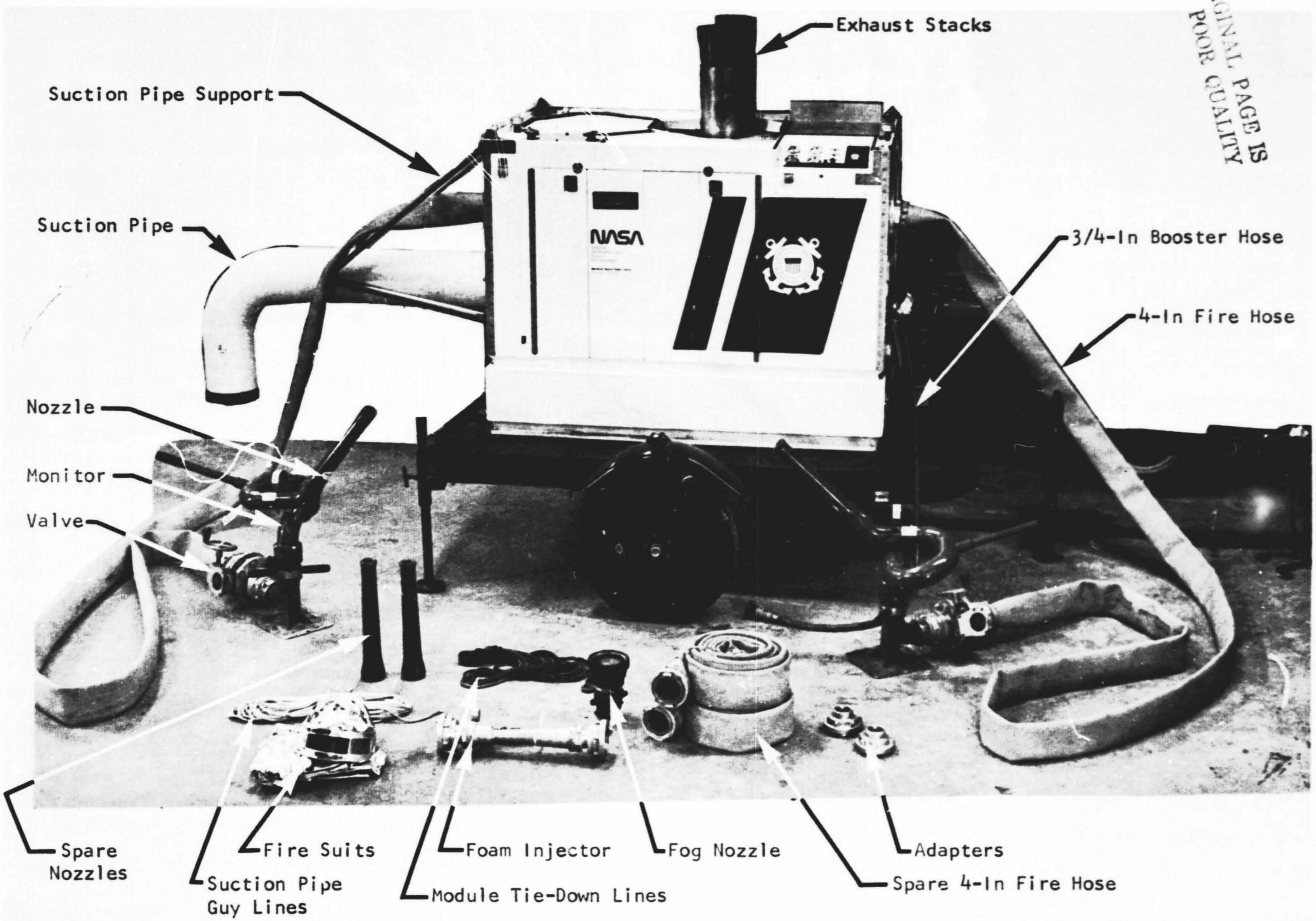


FIGURE 7 - FIREFIGHTING MODULE SETUP WITH EQUIPMENT DEPLOYED

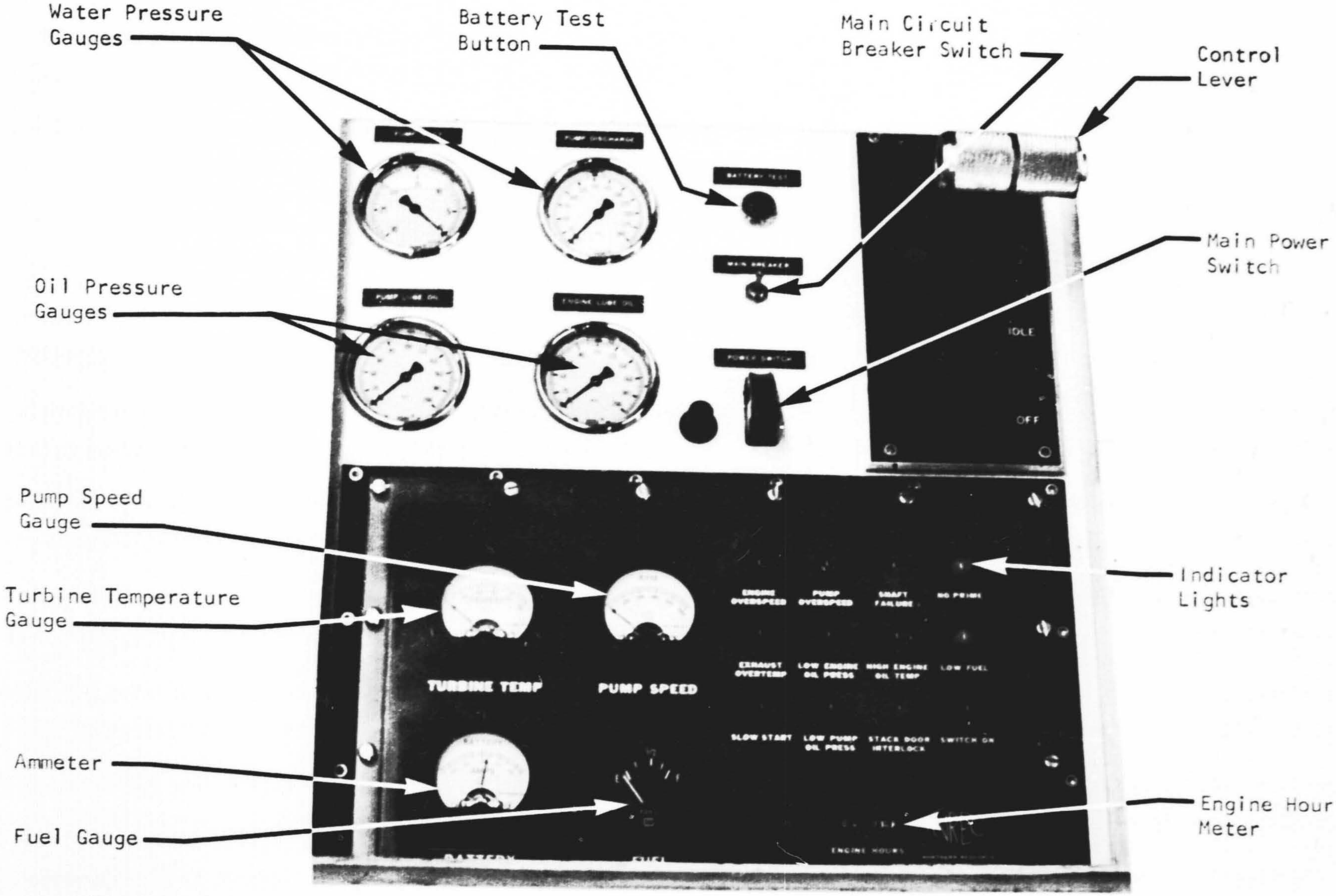


FIGURE 8 - CONTROL PANEL

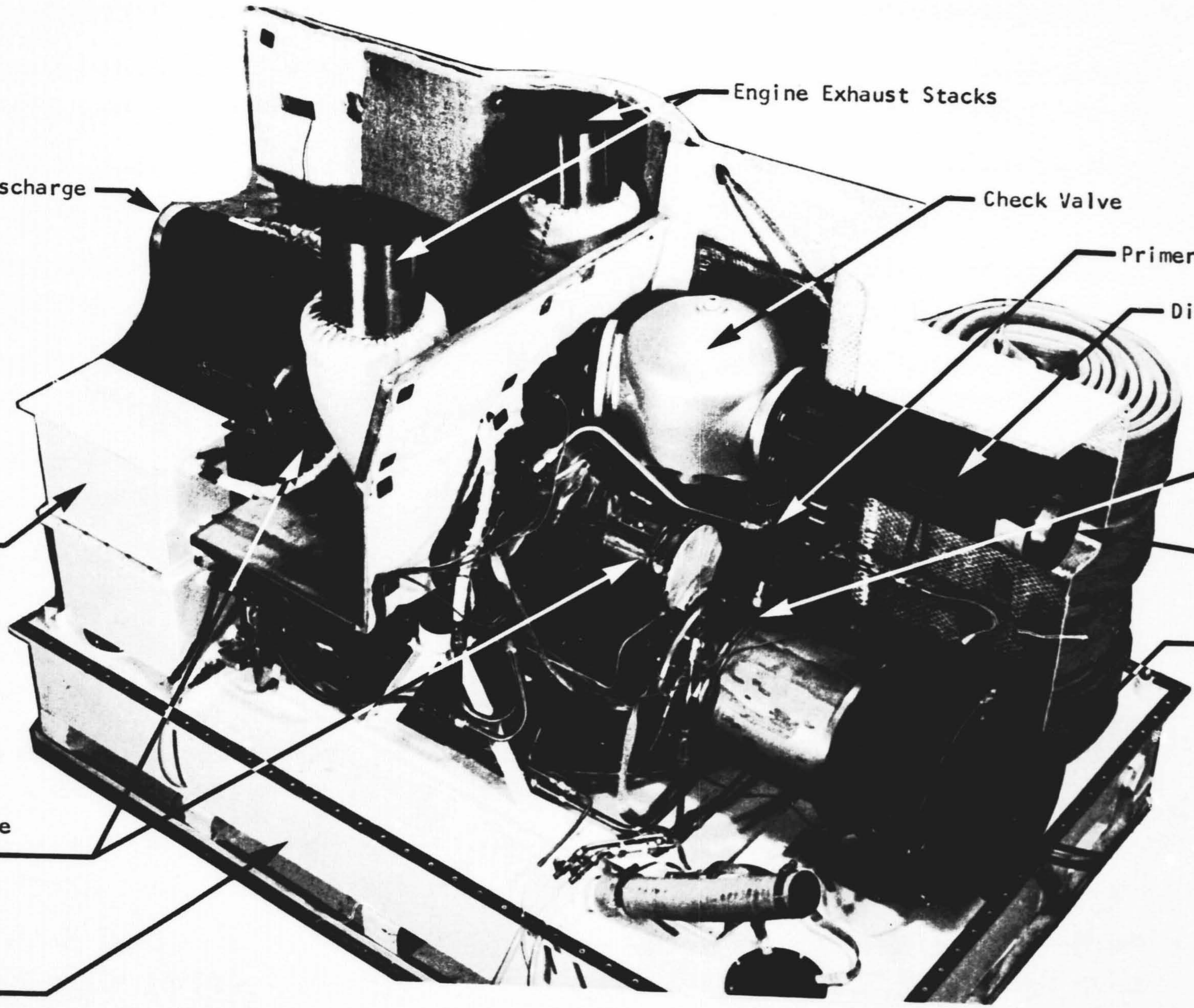


FIGURE 9 - MODULE WITH COVER REMOVED

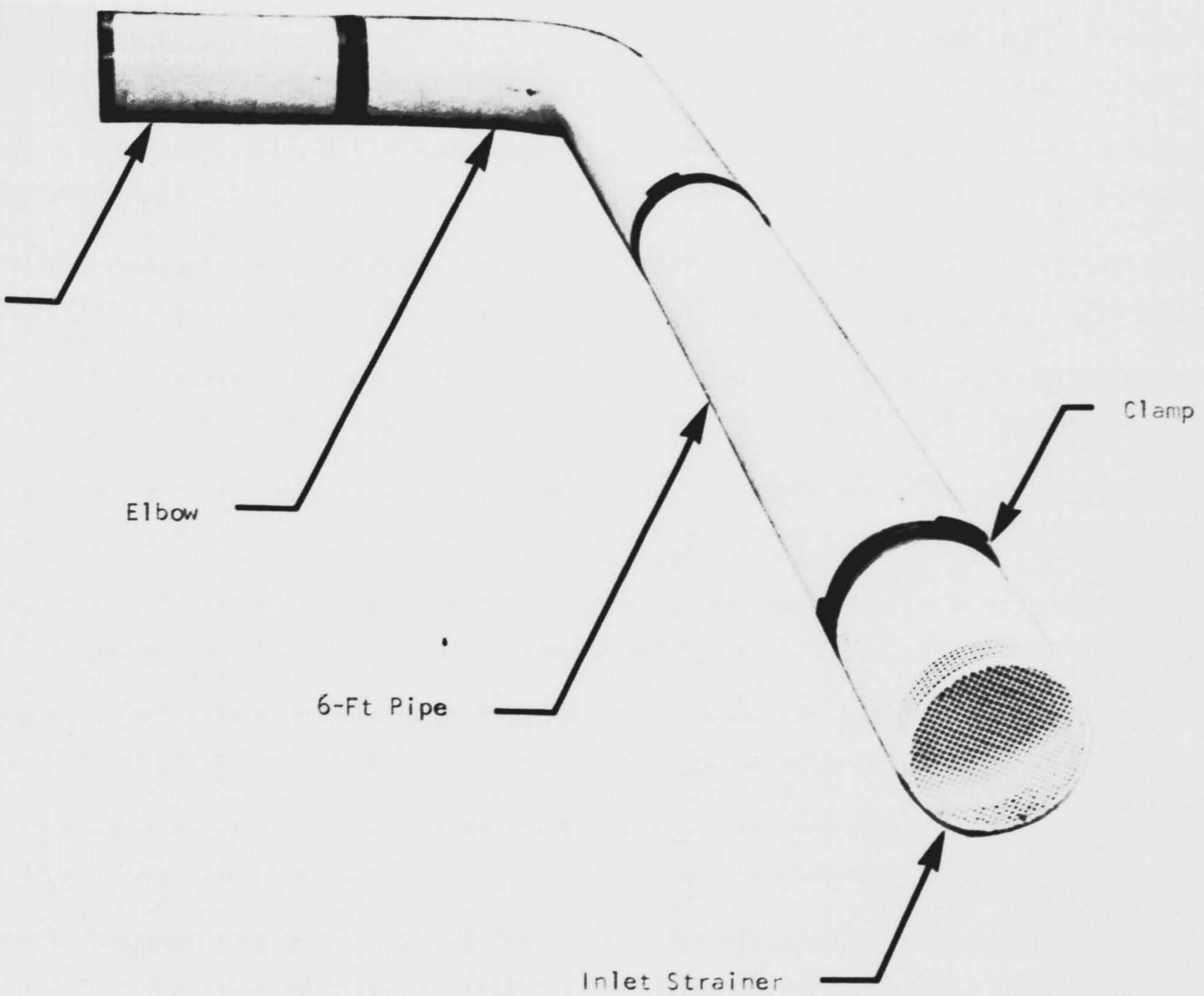


FIGURE 10 - TYPICAL SUCTION PIPE ASSEMBLY

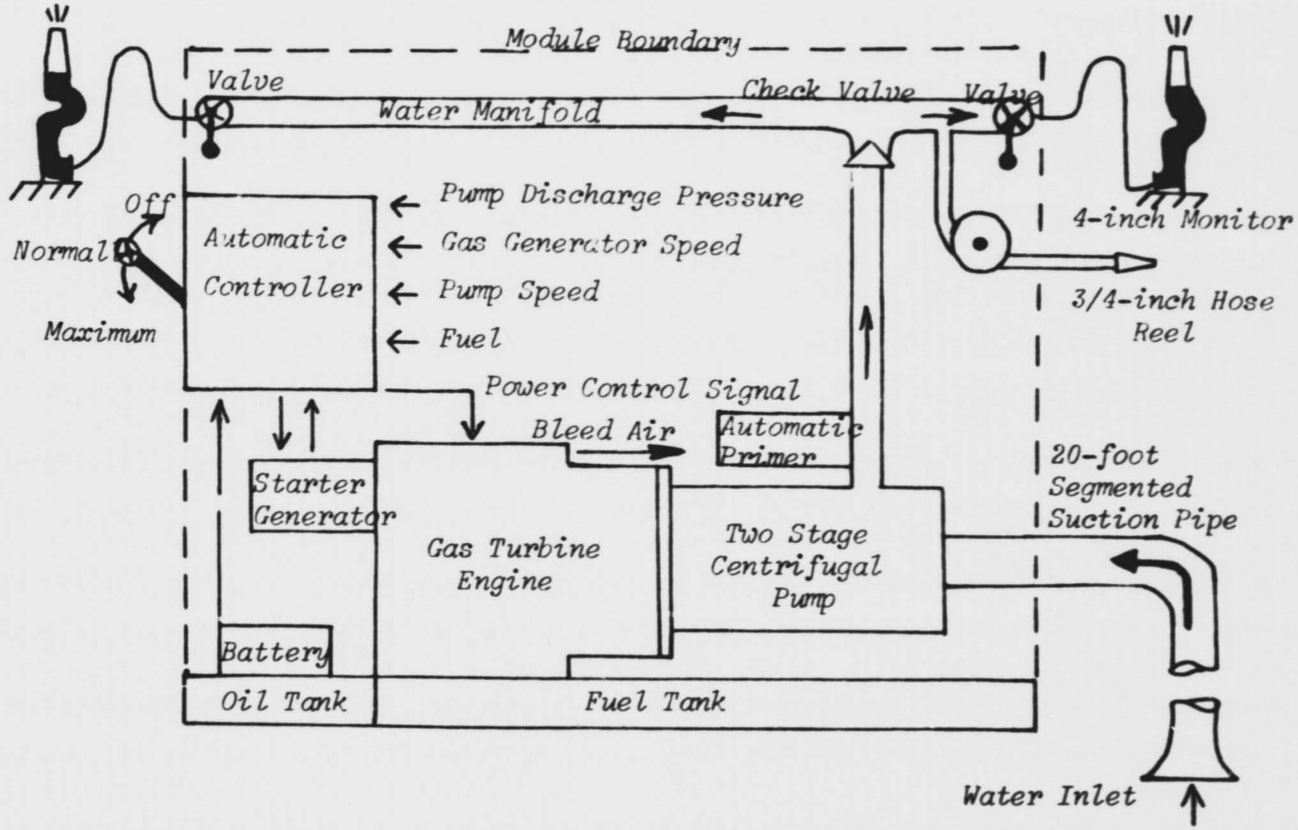
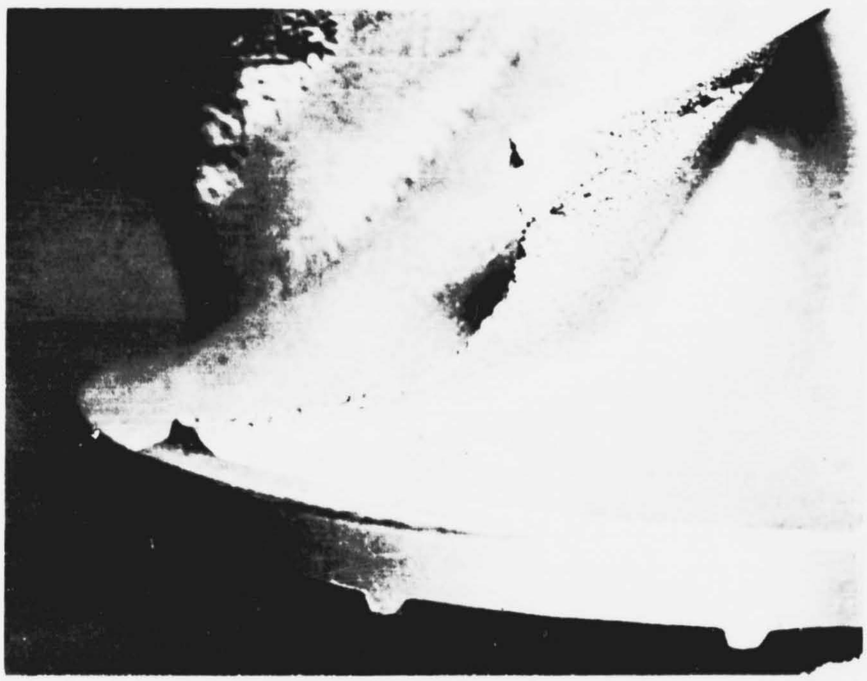


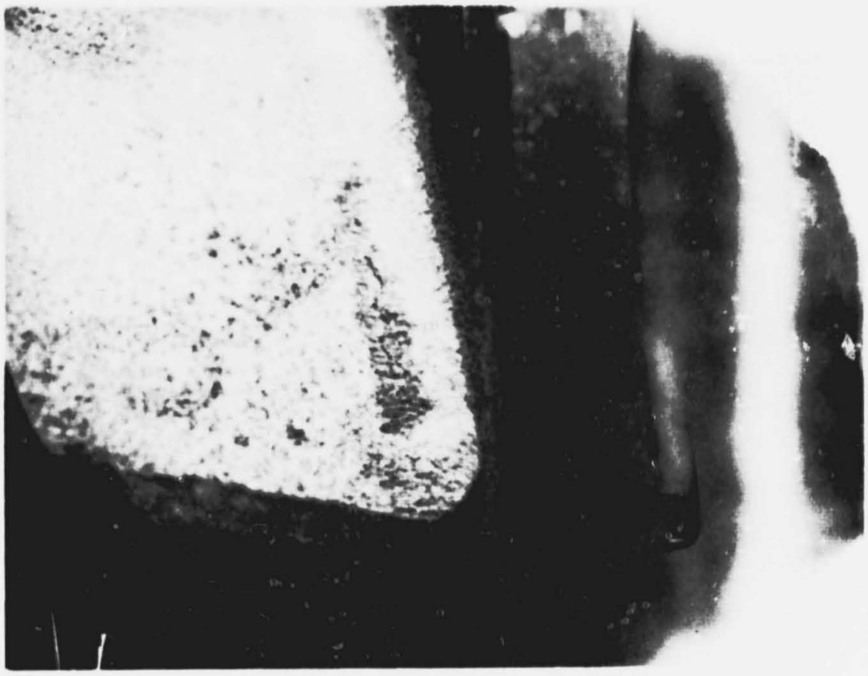
FIGURE 11 - SCHEMATIC DIAGRAM OF FIRE-FIGHTING MODULE

FIGURE 12 - MODULE ON DOLLY



b. Closeup of Broken Vane

FIGURE 13 - PHOTOGRAPHS OF MAIN IMPELLER
AFTER 45 HOURS ENDURANCE TEST



c. Fatigue crack, root of blade near tip

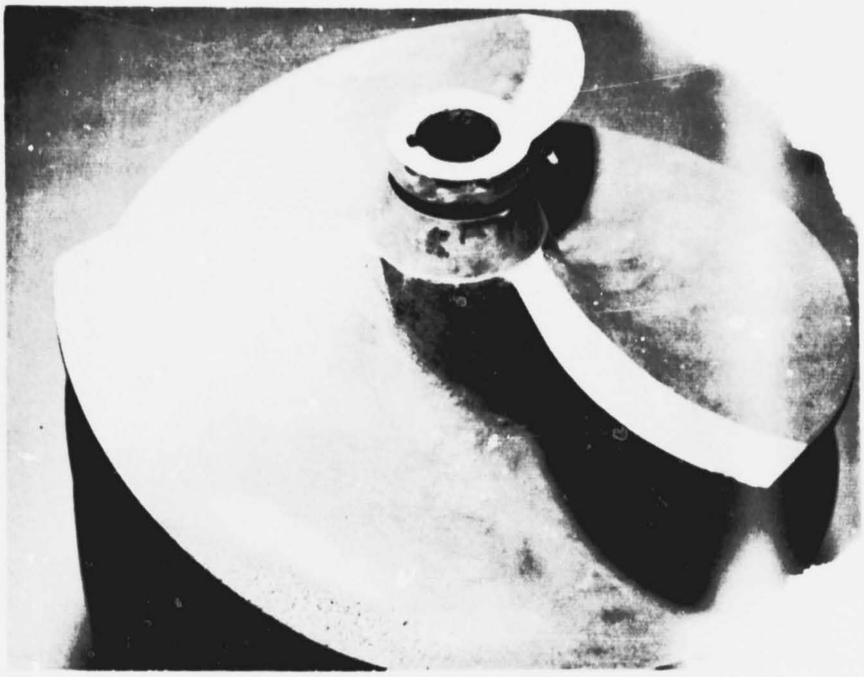
d. Cavitation damage, pressure surface

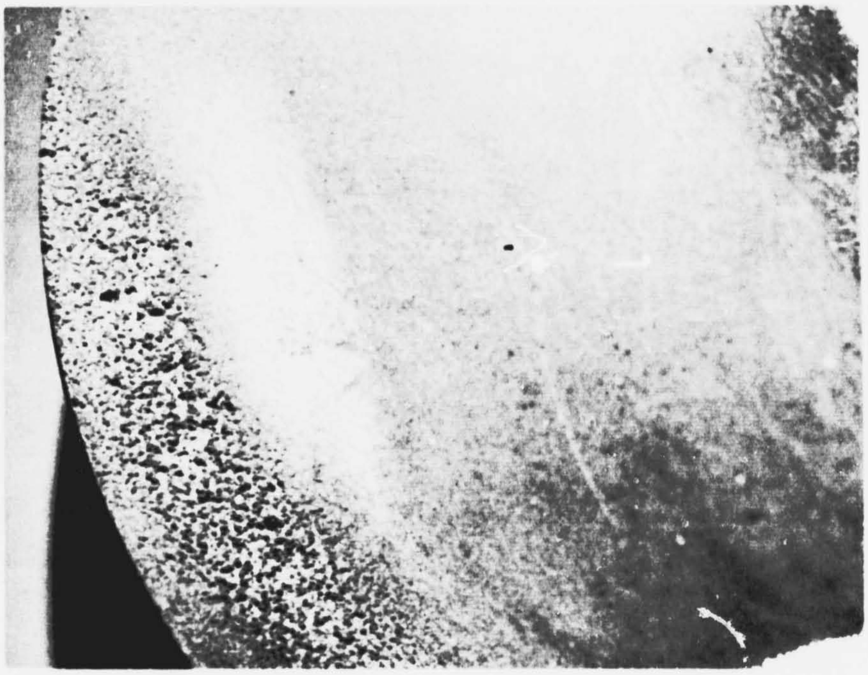
FIGURE 13 (CONTINUED) - PHOTOGRAPHS OF MAIN IMPELLER AFTER 45 HOURS ENDURANCE TEST

c. Cavitation damage, suction surface root

f. Breakthrough into suction surface

FIGURE 13 (CONTINUED) - PHOTOGRAPHS OF MAIN IMPELLER AFTER 45 HOURS ENDURANCE TEST





b. Closeup of Cavitation Damage

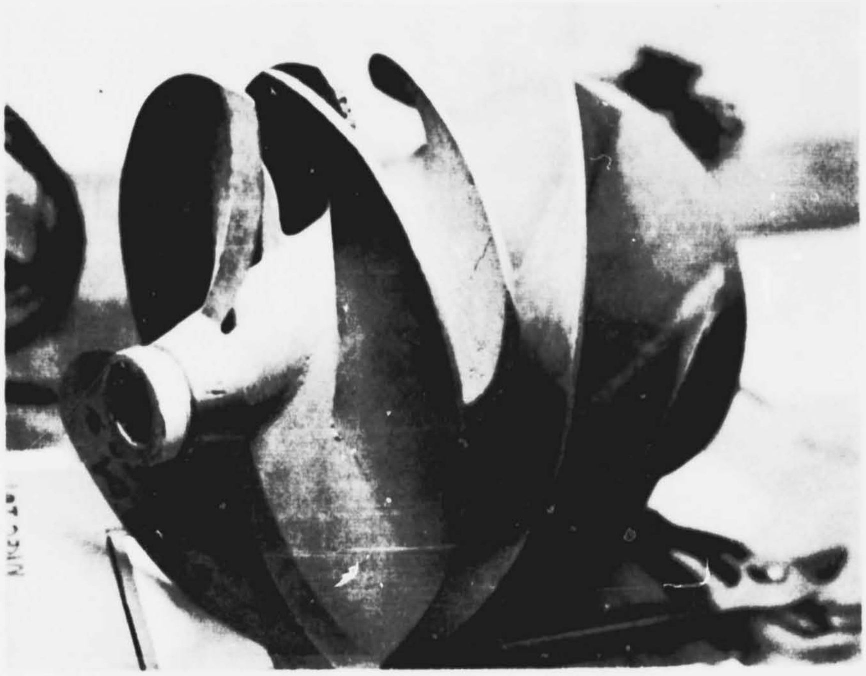
FIGURE 14 - PHOTOGRAPHS OF INDUCER IMPELLER
AFTER 45 HOURS ENDURANCE TEST

a. Pressure Surface

b. Suction Surface

FIGURE 15 - CAVITATION DAMAGE TO MAIN IMPELLER

FIGURE 16 - CAVITATION DAMAGE TO INDUCER IMPELLER



a. General View

b. Closeup of Fracture

FIGURE 17 - INDUCER AFTER BLADE FAILURE

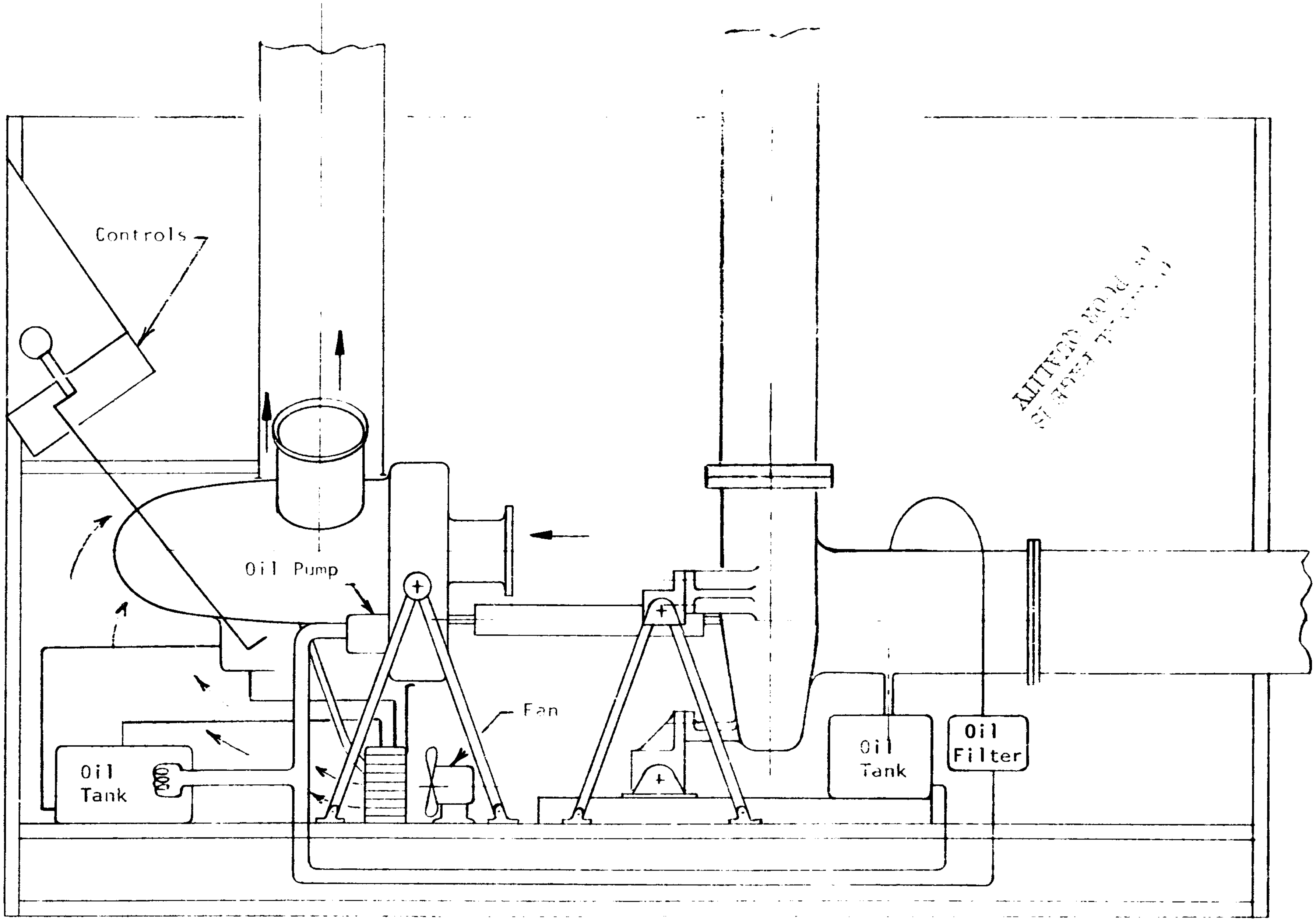


FIGURE 18 - TEST RIG SCHEMATIC

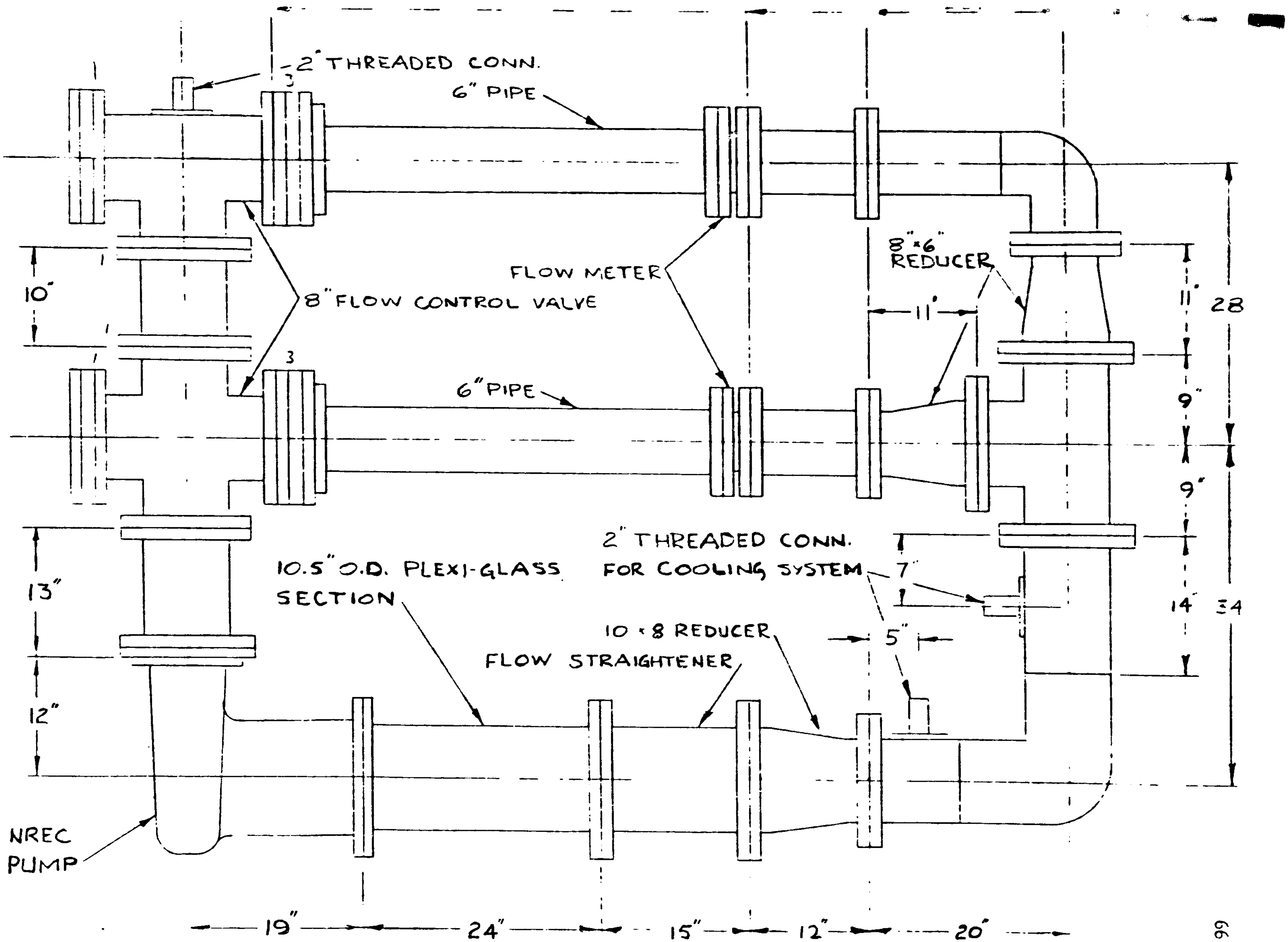


FIGURE 19 - WATER TEST LOOP

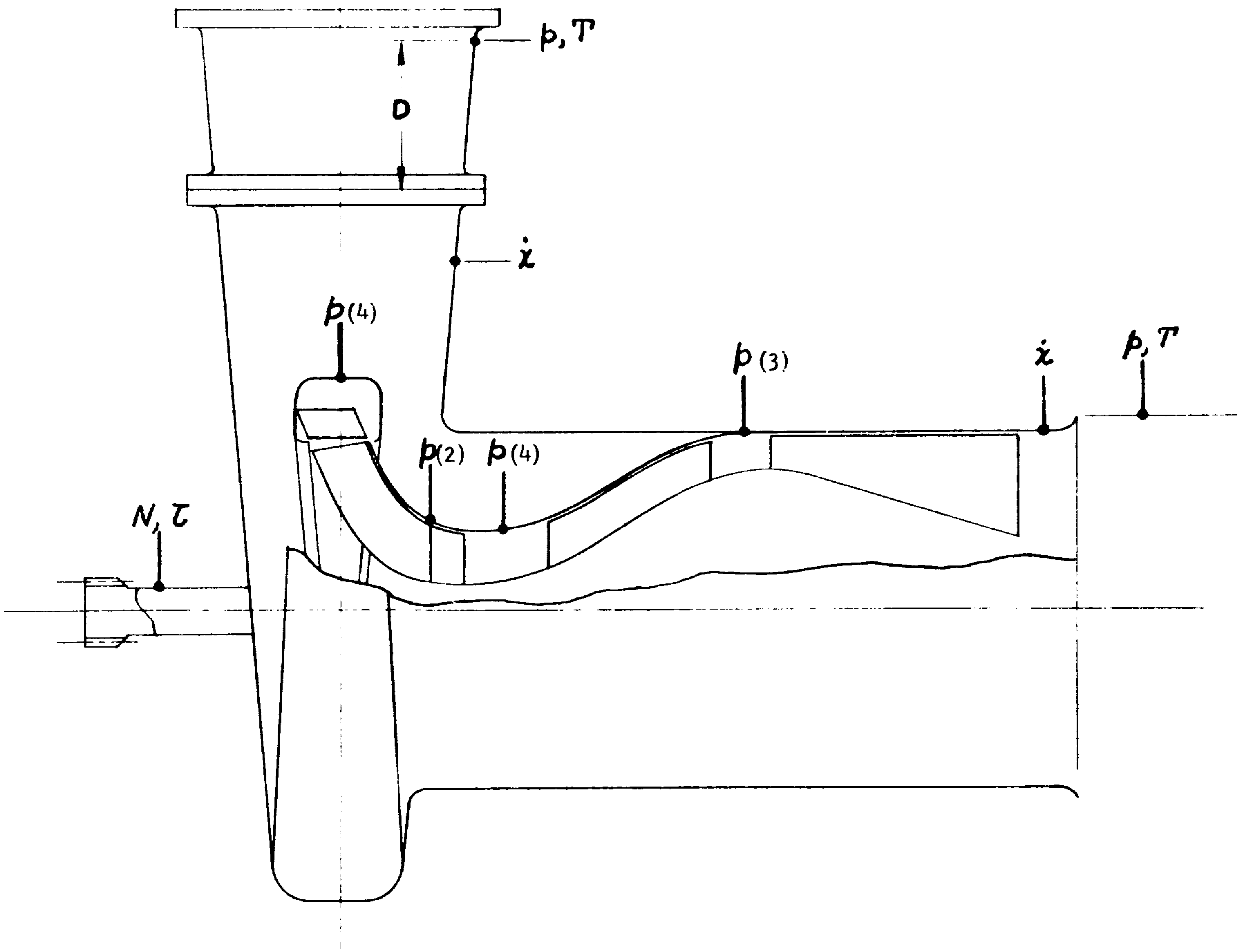


FIGURE 20 - PUMP TEST INSTRUMENTATION SCHEMATIC

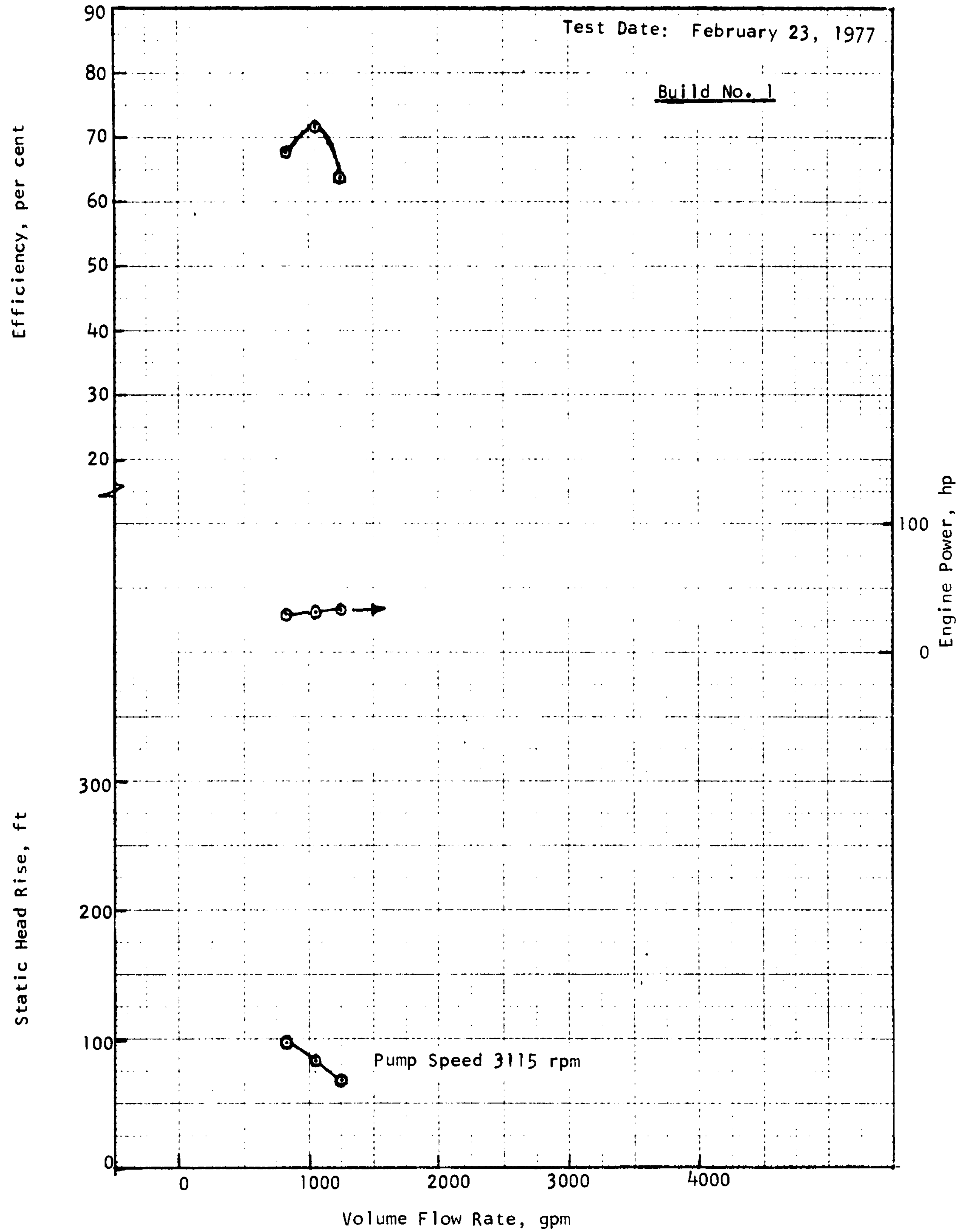


FIGURE 21 - MEASURED PUMP PERFORMANCE AT HALF SPEED

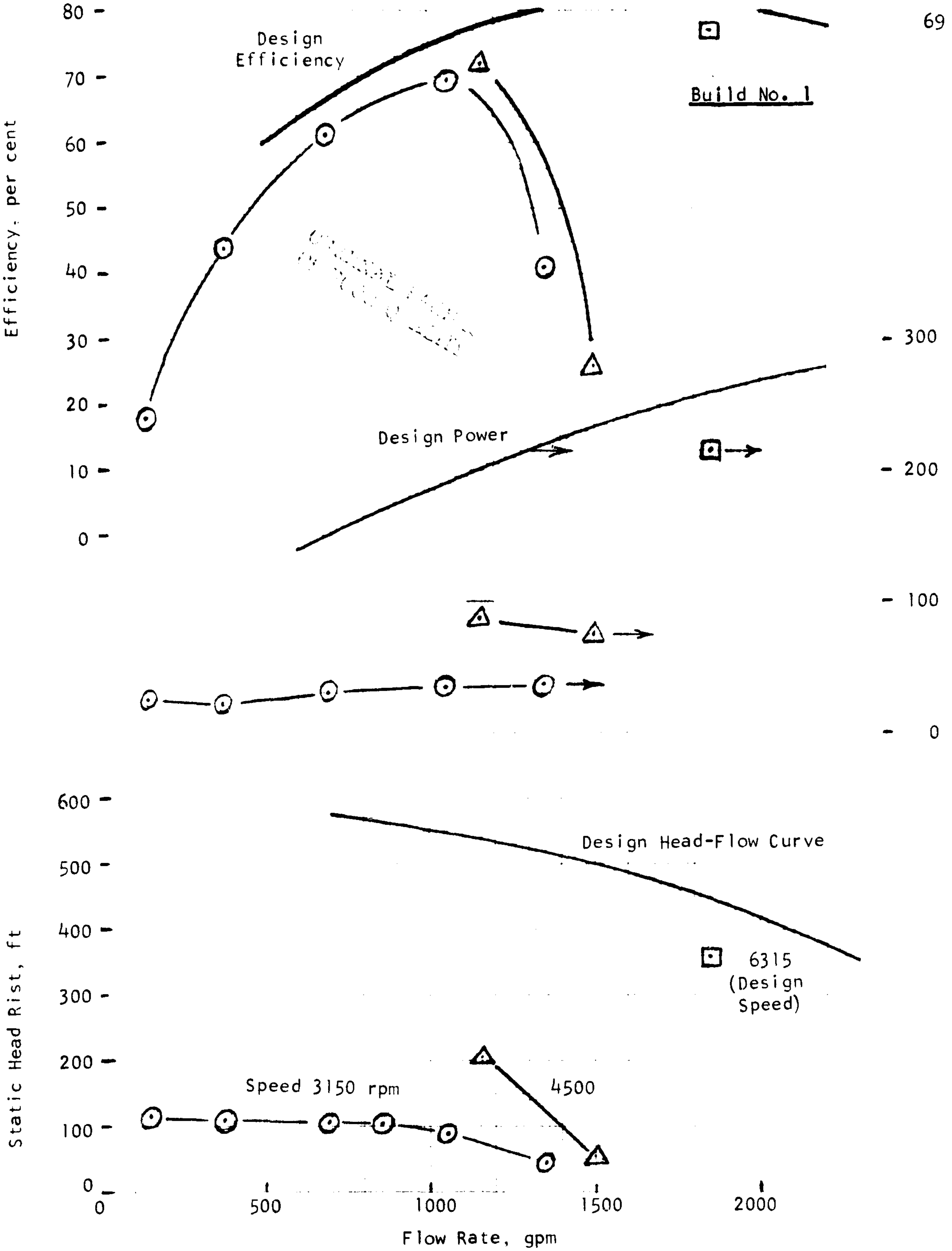


FIGURE 22 - MEASURED PERFORMANCE OF PUMP COMPARED TO DESIGN PERFORMANCE

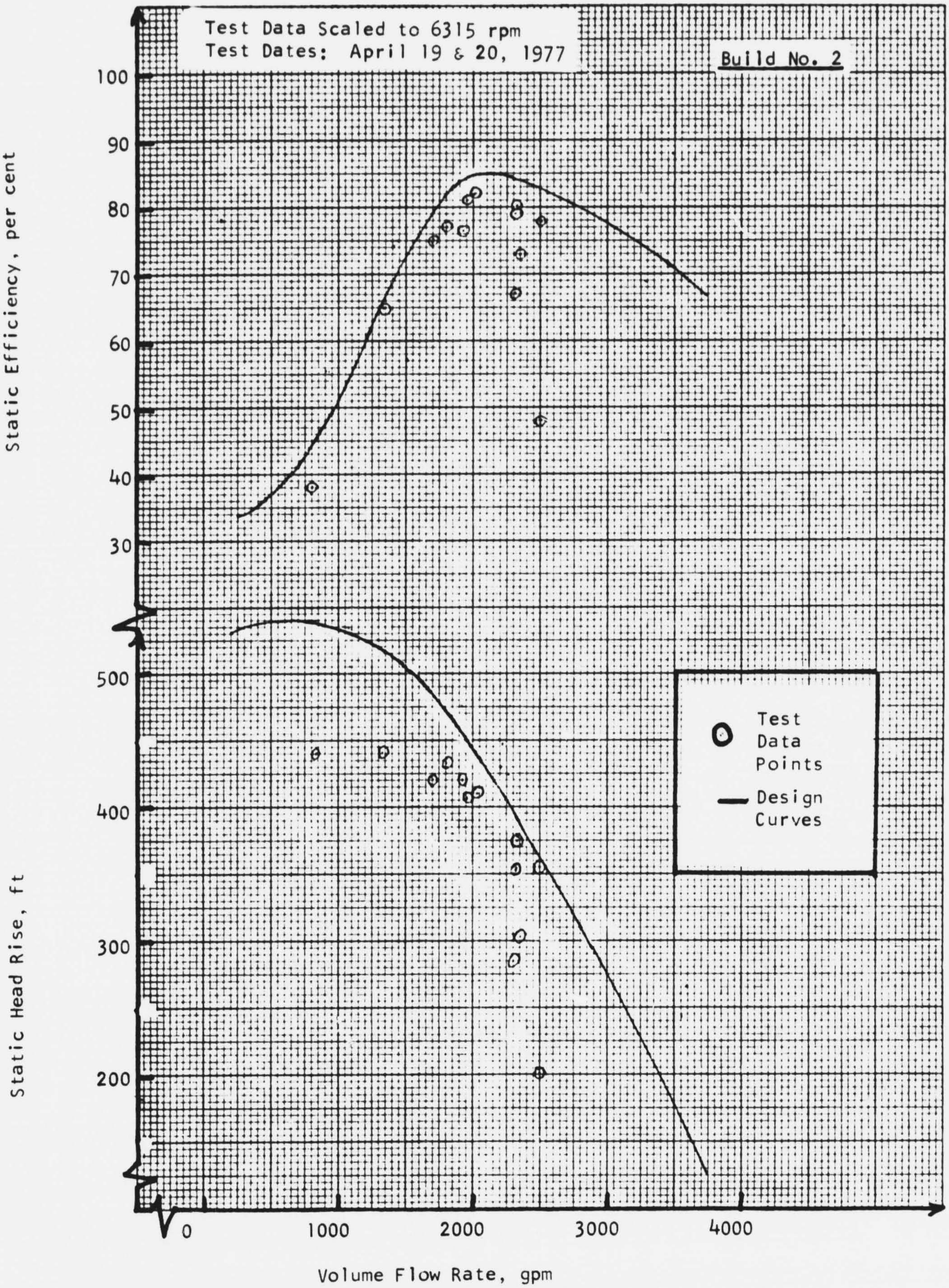


FIGURE 23 - MEASURED PERFORMANCE OF PUMP COMPARED TO DESIGN PERFORMANCE

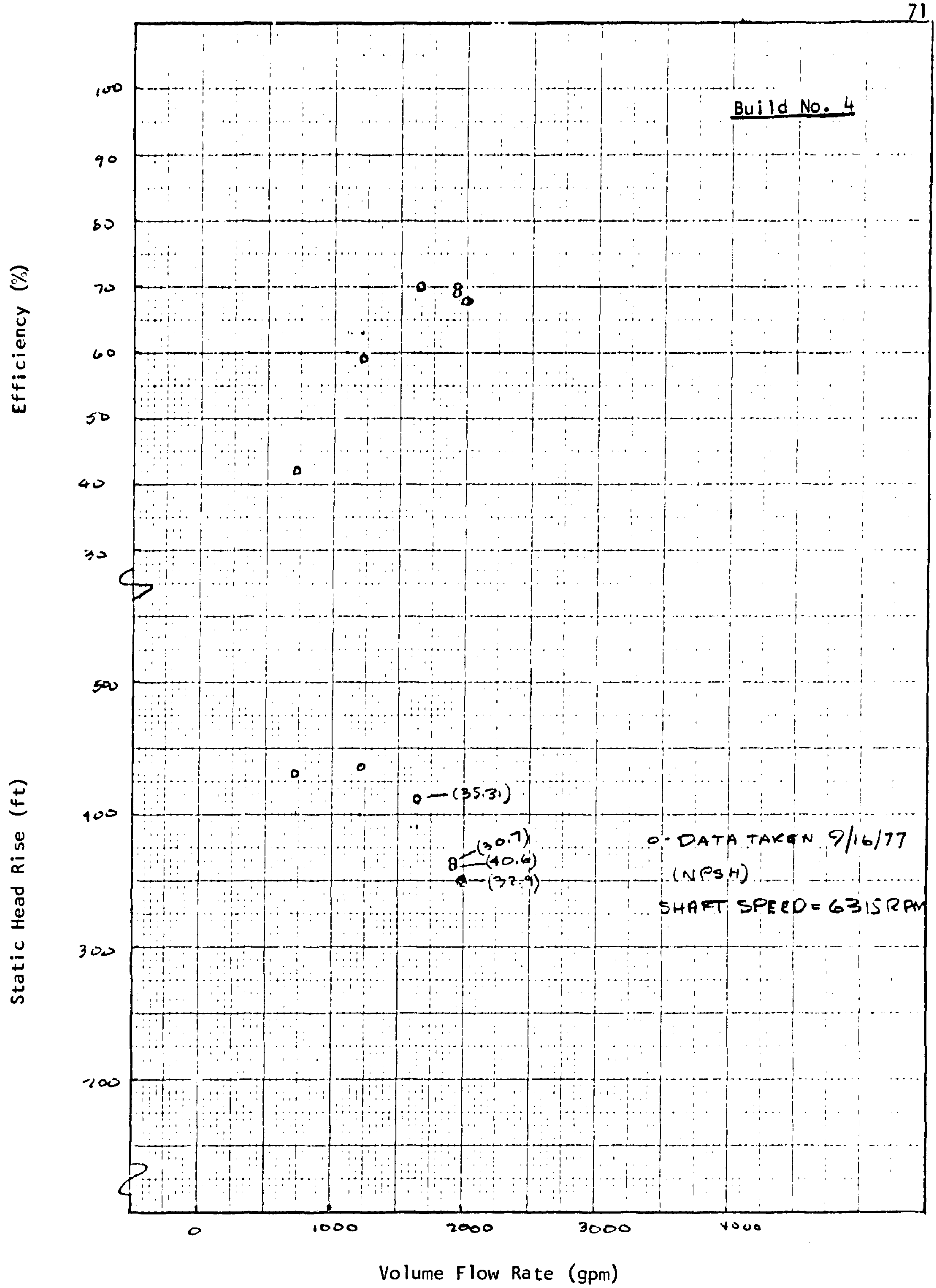


FIGURE 24 - PERFORMANCE DATA FOR PUMP BUILD 4

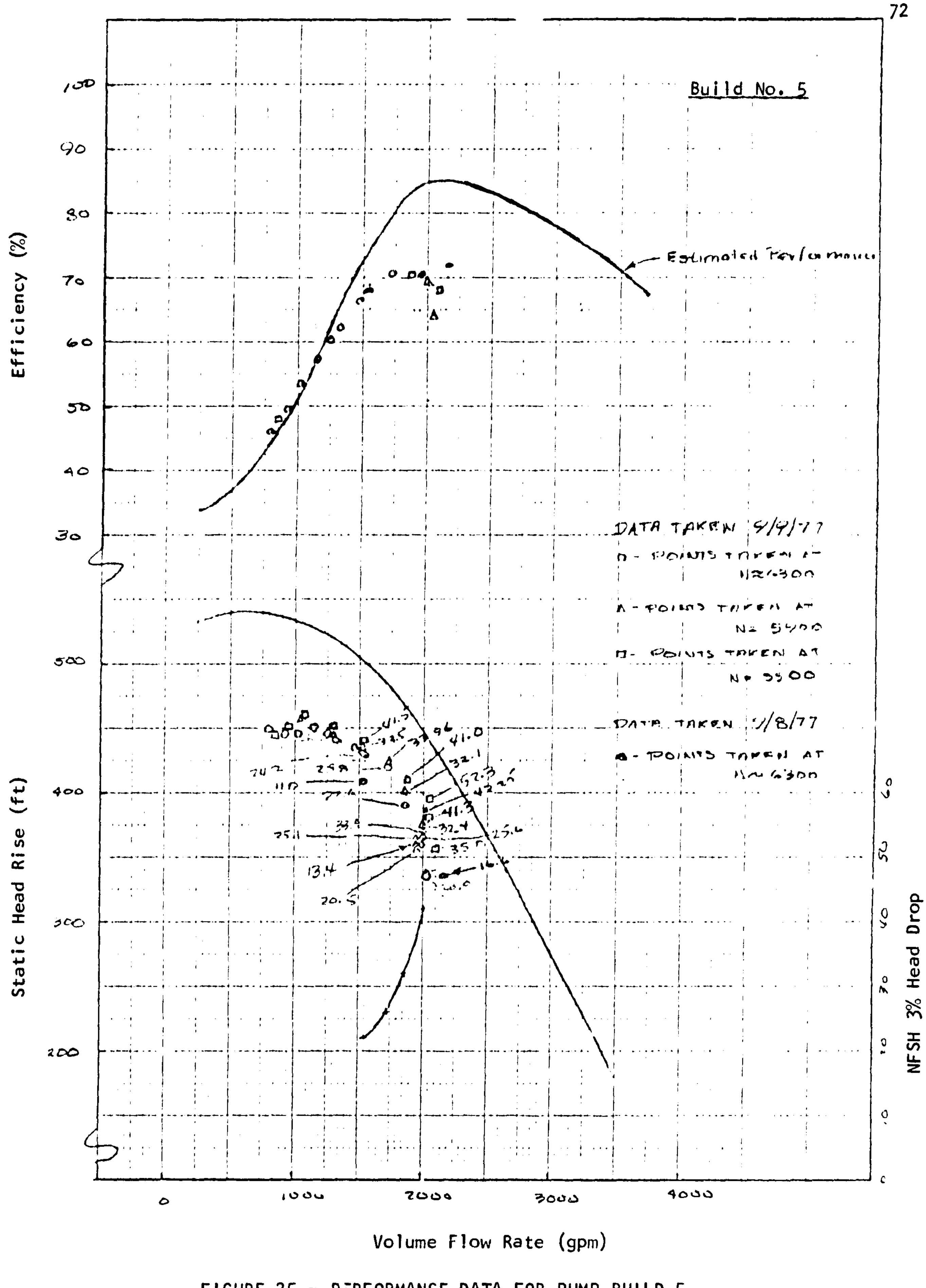


FIGURE 25 - PERFORMANCE DATA FOR PUMP BUILD 5

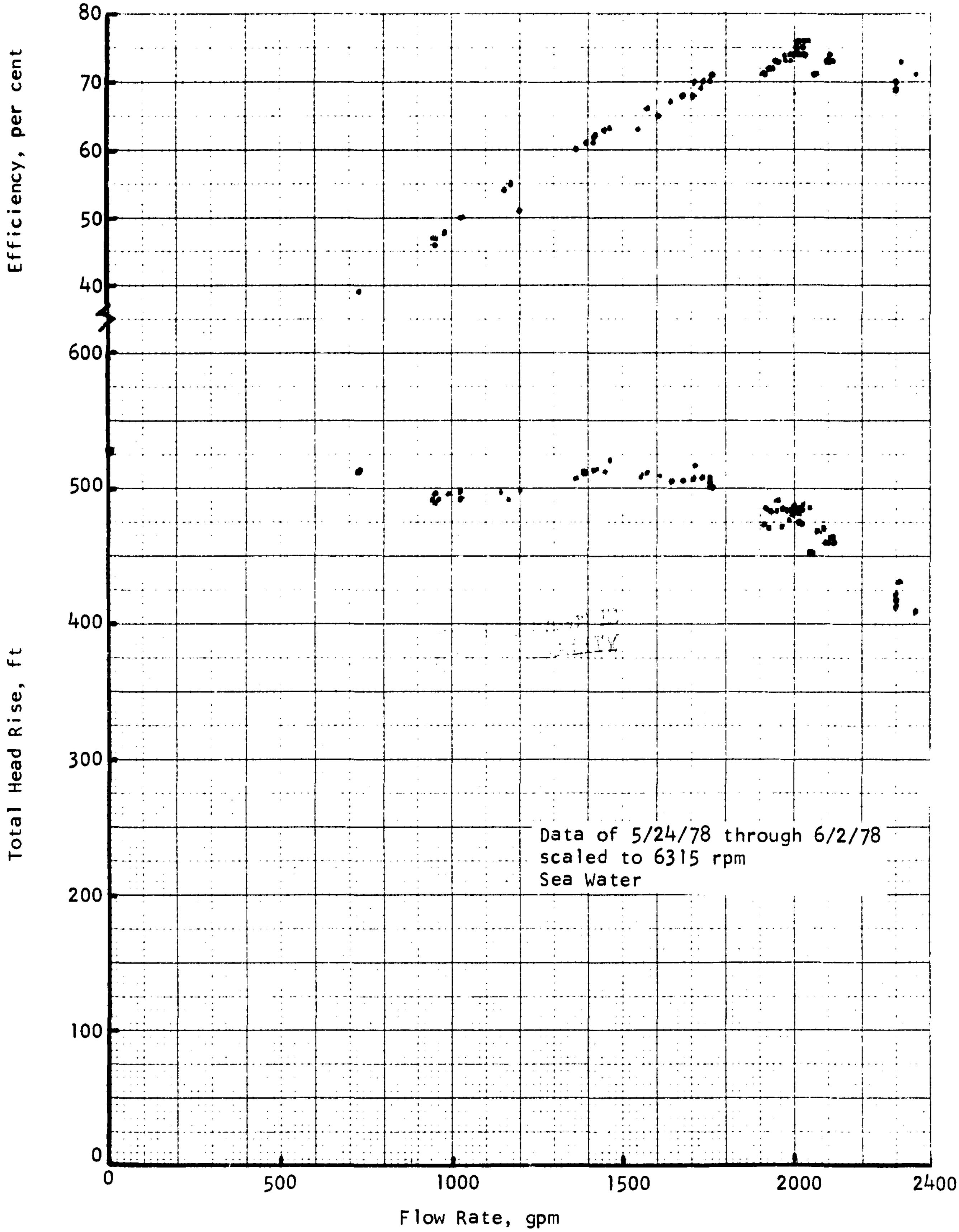


FIGURE 26 - PUMP PERFORMANCE

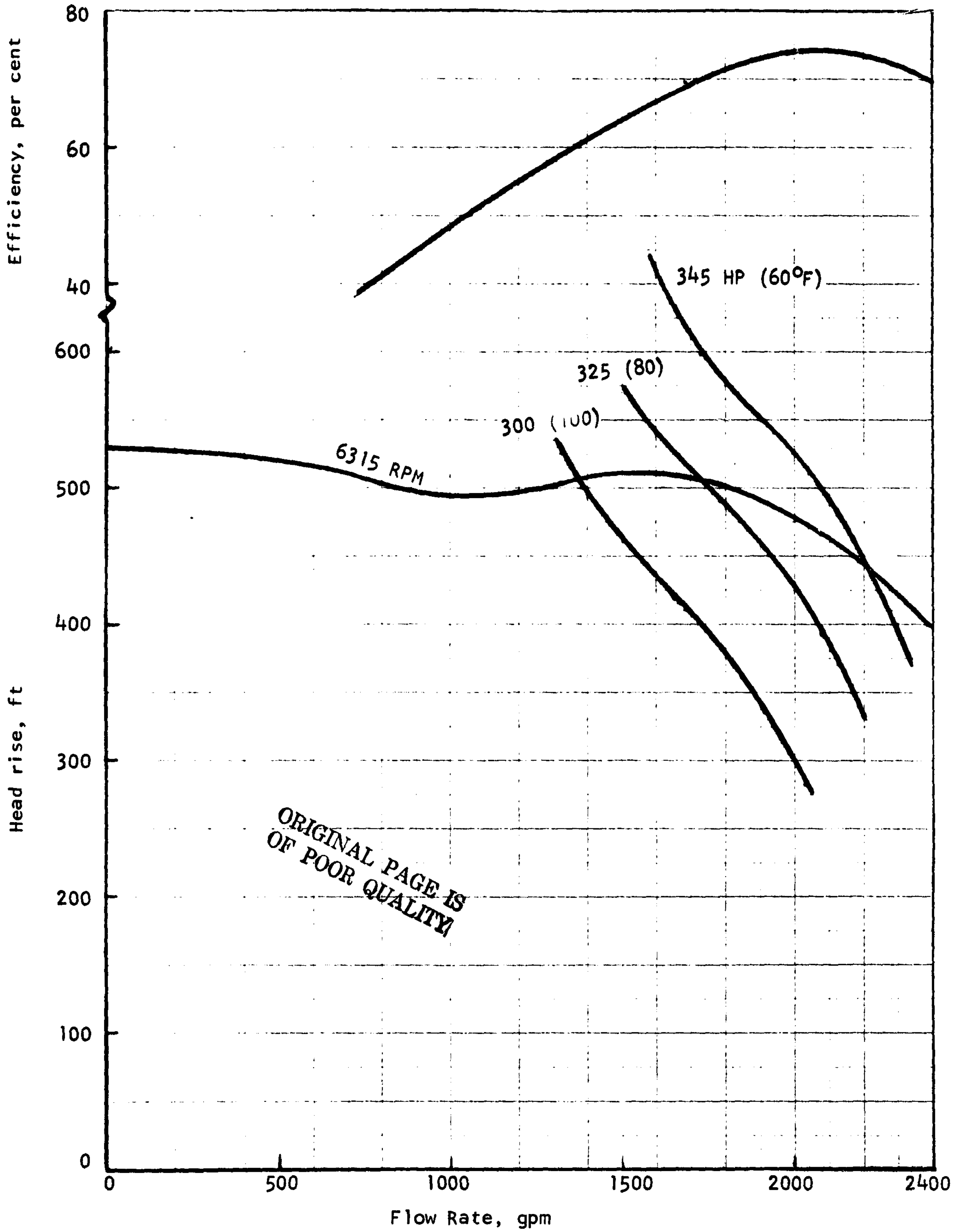


FIGURE 27 - EFFECT OF AMBIENT TEMPERATURE ON ENGINE POWER AND PUMP PERFORMANCE

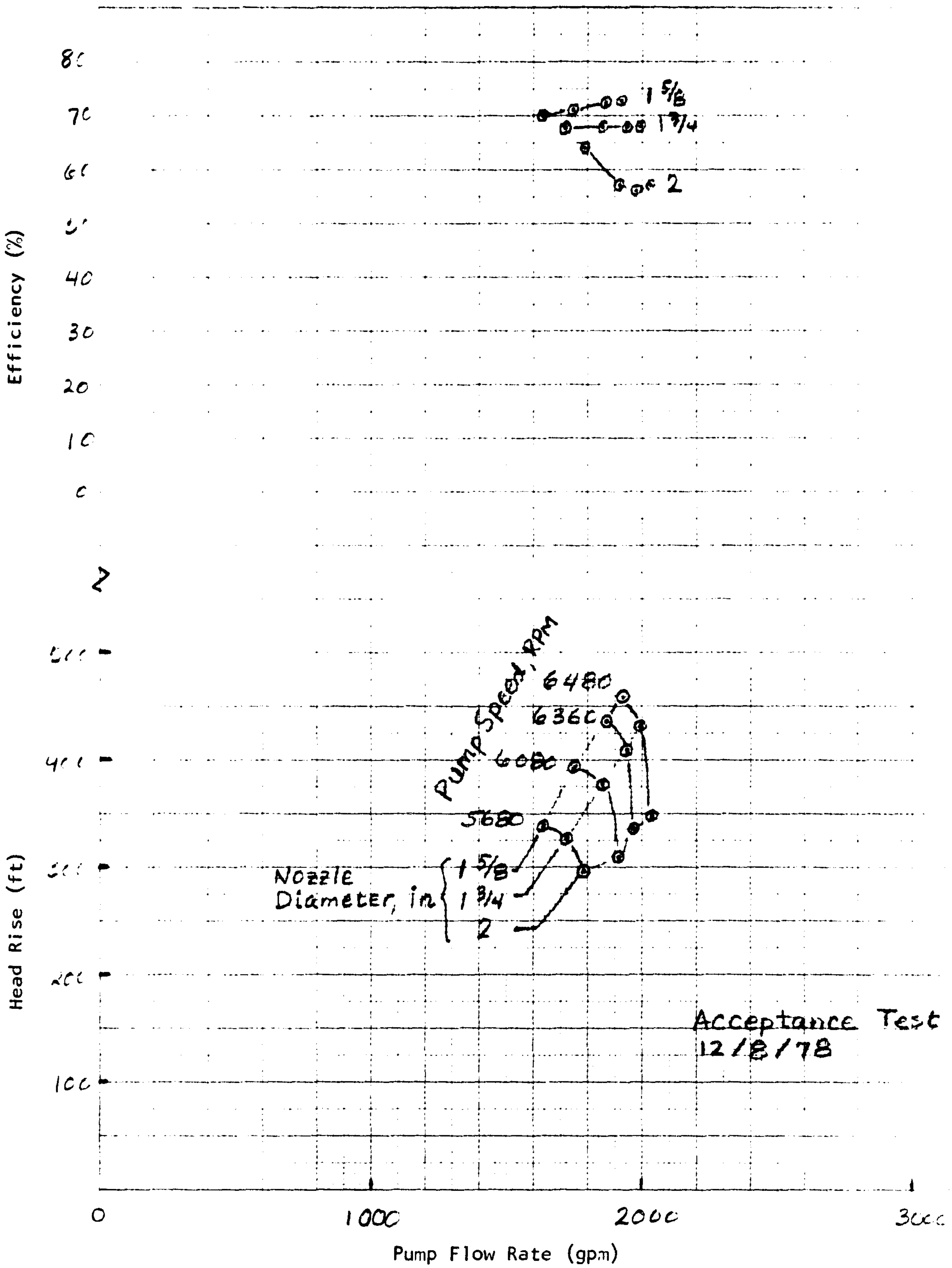


FIGURE 28 - PUMP PERFORMANCE

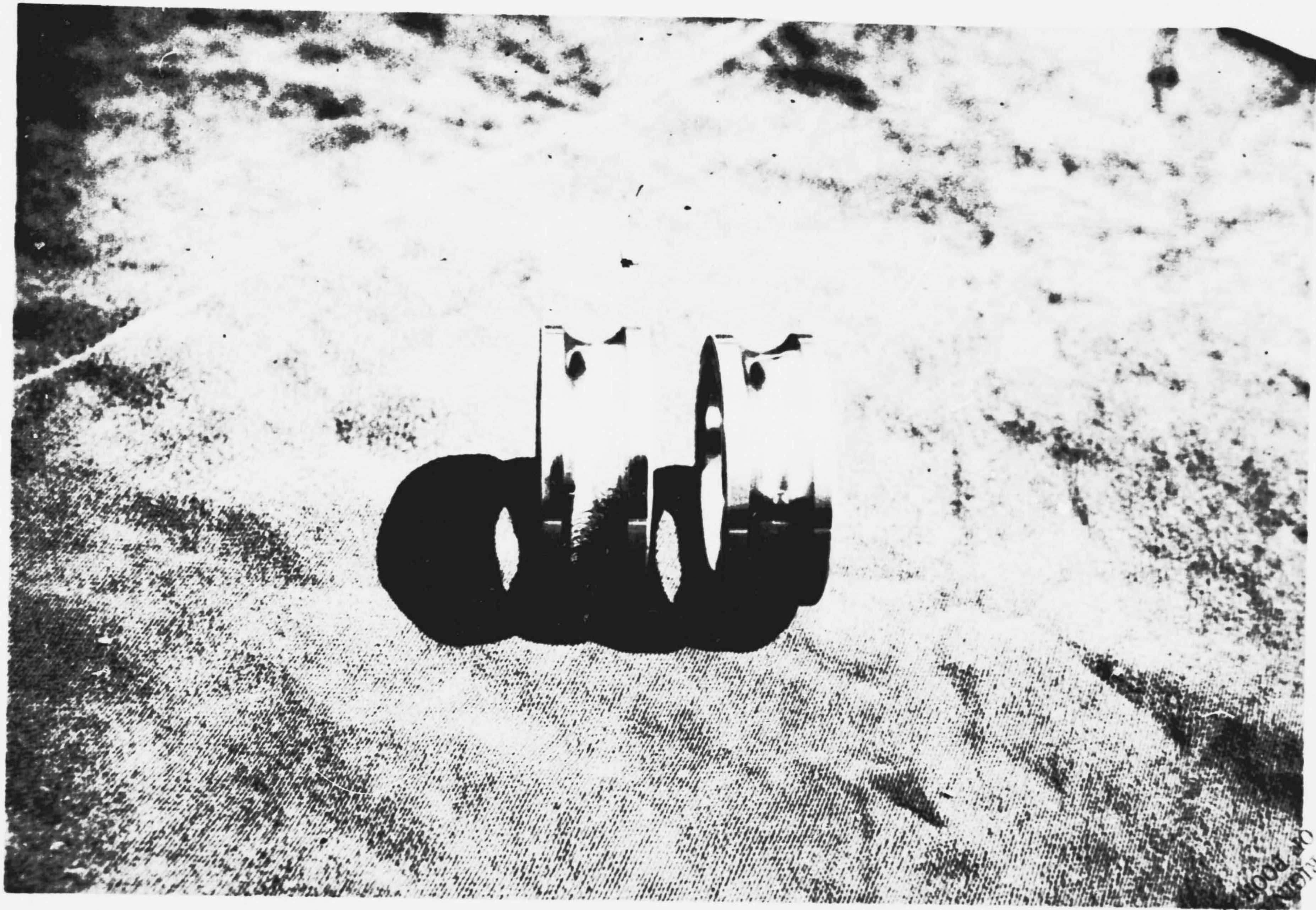


FIGURE 29 - MAIN IMPELLER BEARING INNER RACE

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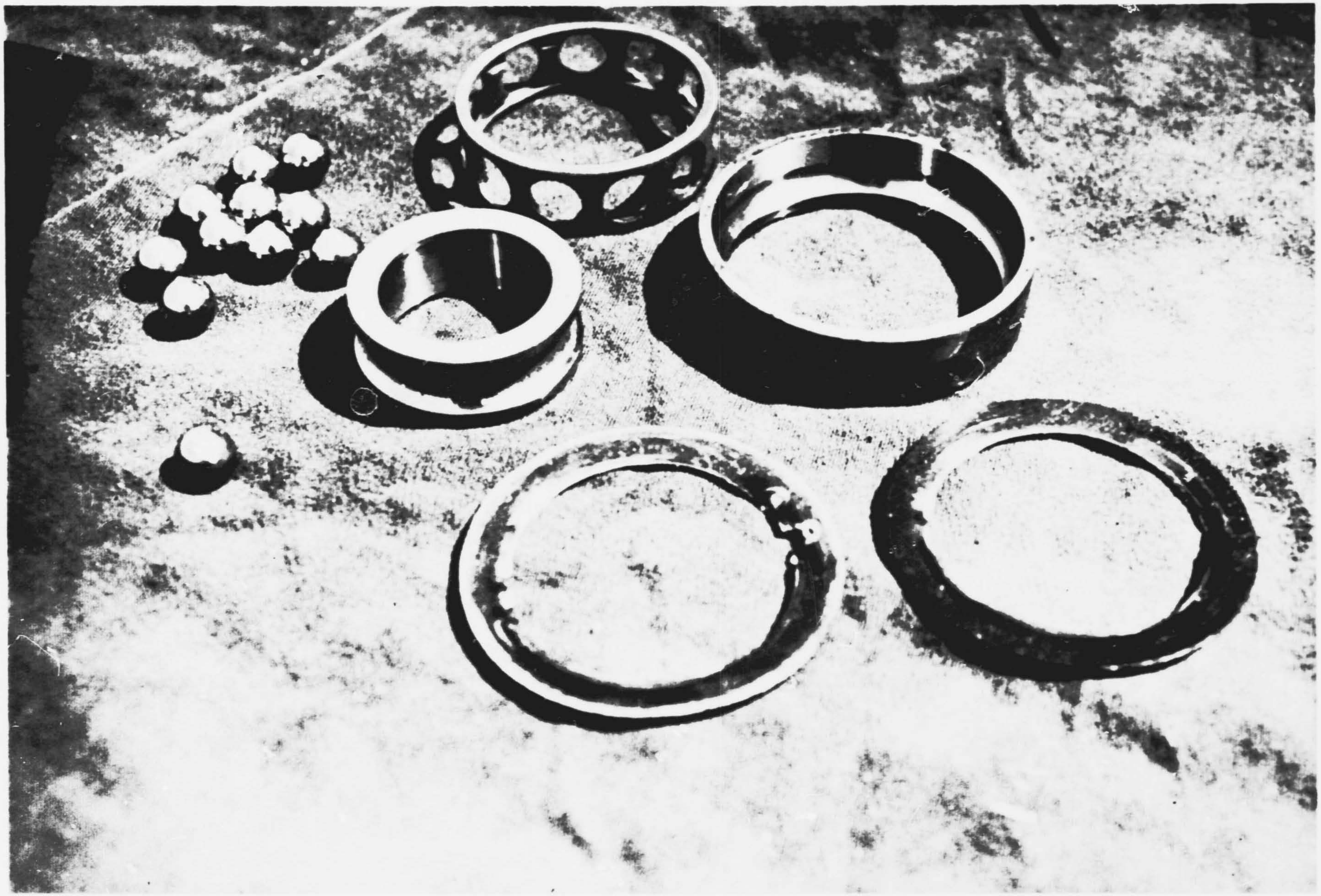

FIGURE 30 - MAIN IMPELLER BEARING AND BELLVILLE WASHERS

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OF POOR QUALITY

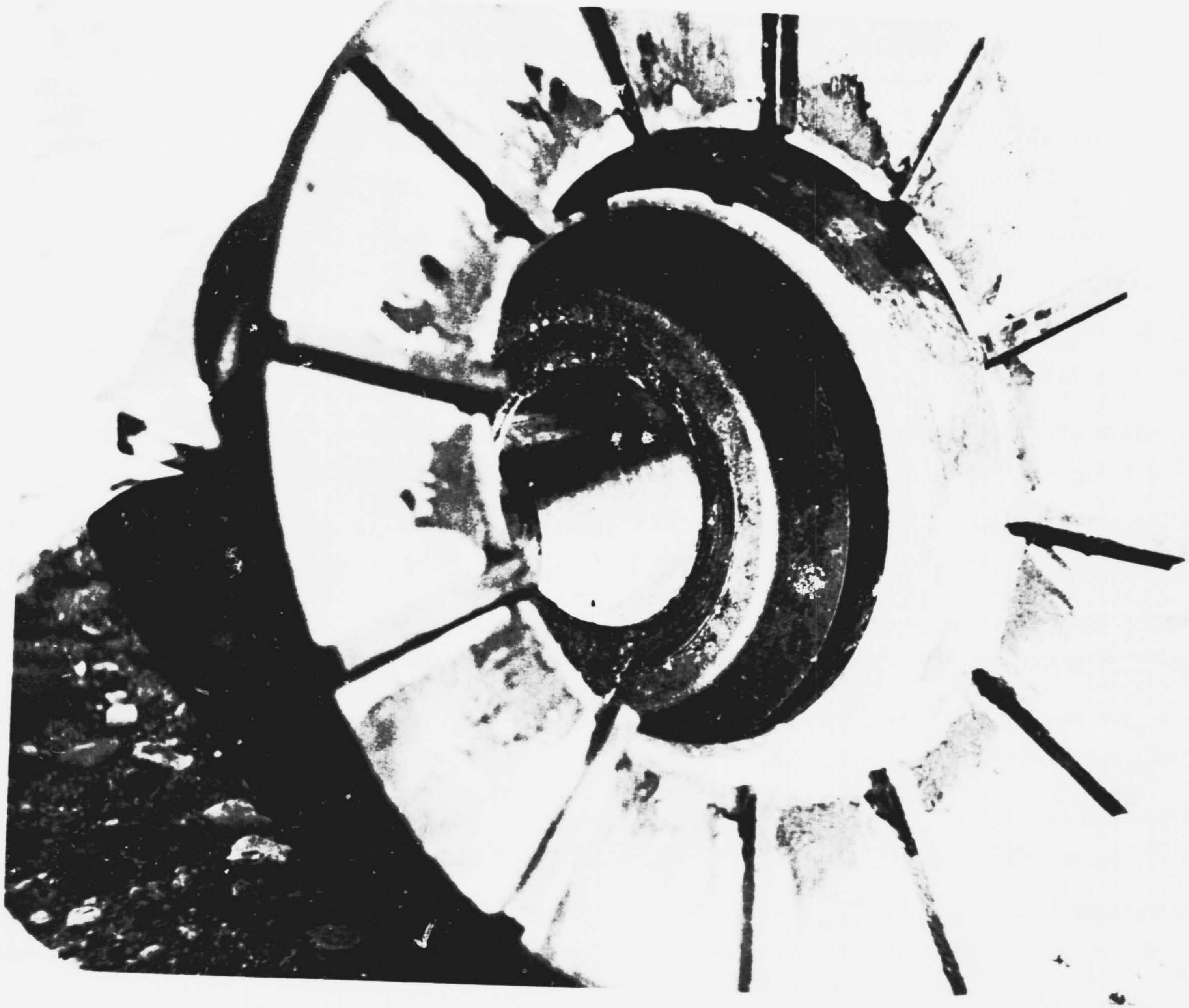

FIGURE 31 - MAIN IMPELLER

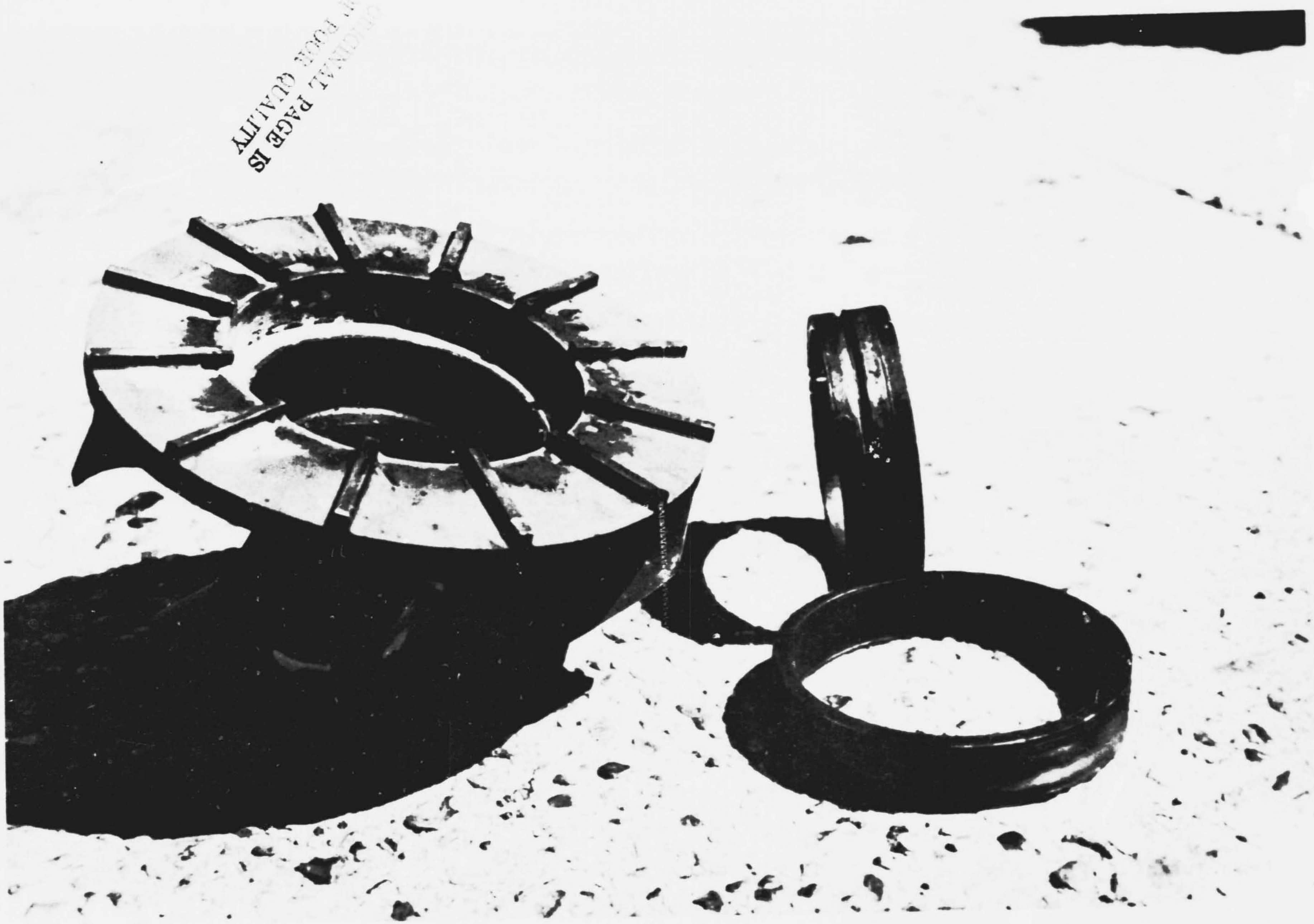

FIGURE 32 - MAIN IMPELLER AND SEAL RING

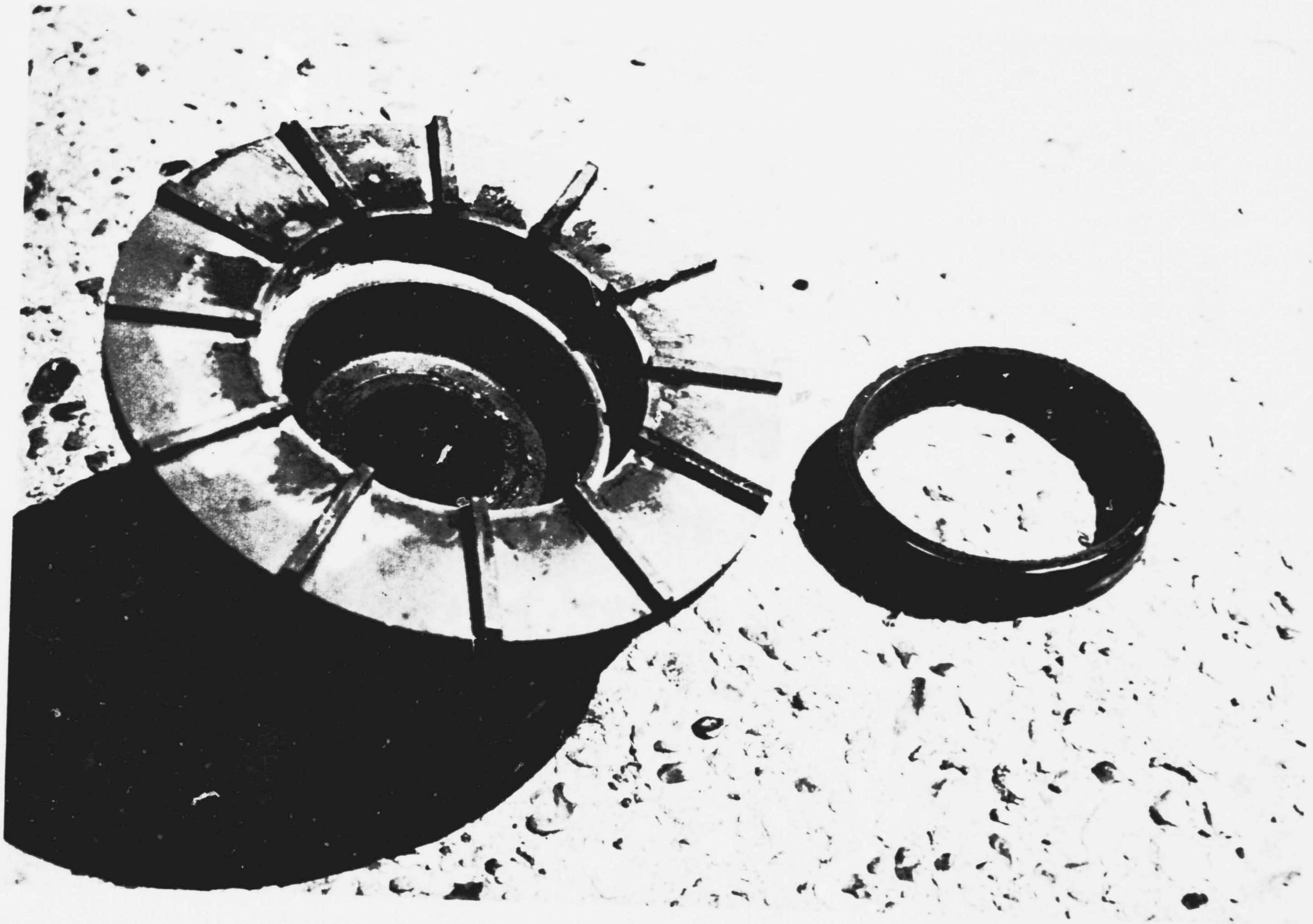

FIGURE 33 - MAIN IMPELLER AND SEAL RING

FIGURE 34 - MAIN IMPELLER, CAVITATION POLISHING

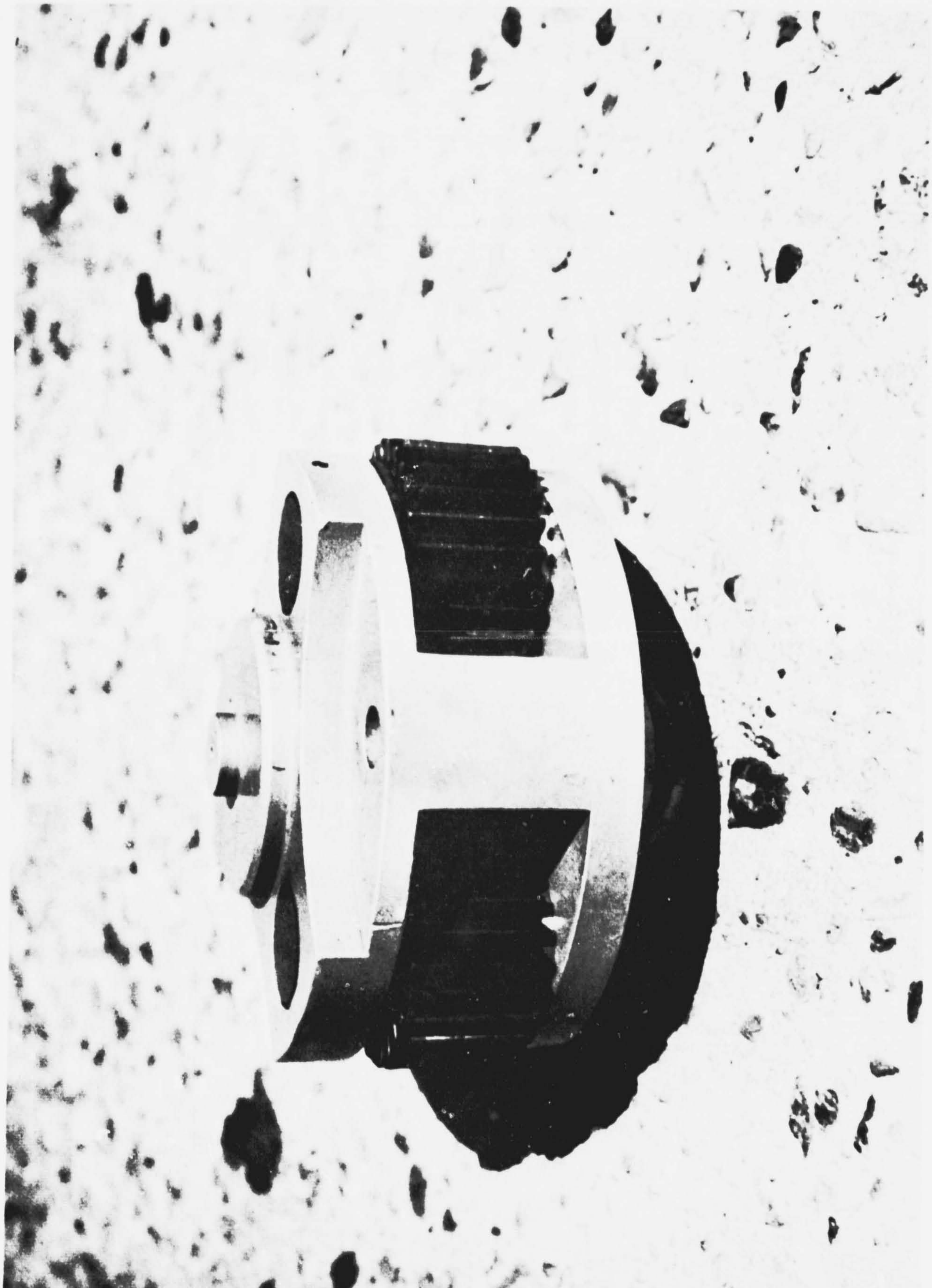

FIGURE 35 - GEARBOX

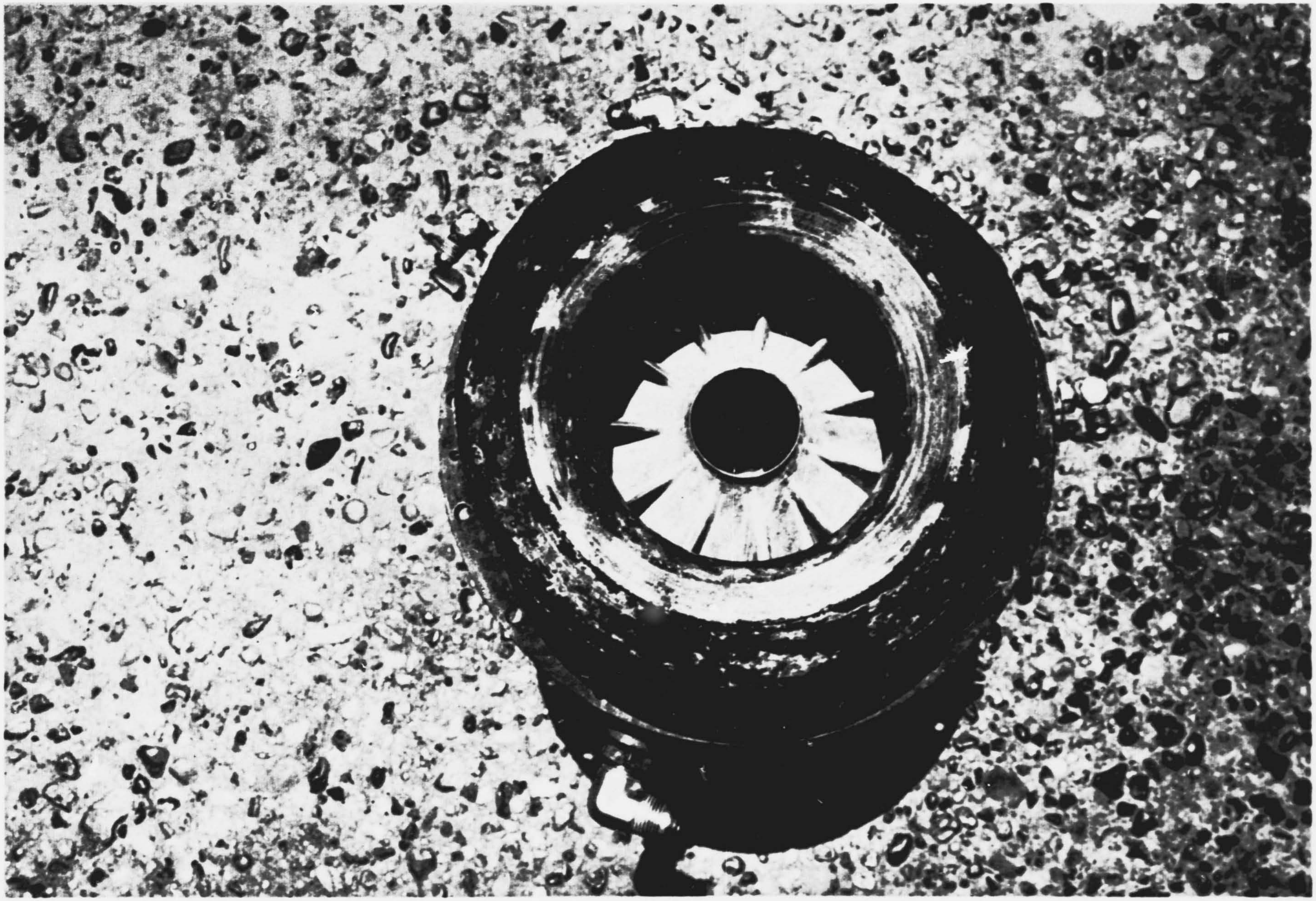

FIGURE 36 - INDUCER HOUSING, MAIN IMPELLER SHROUD

FIGURE 37 - VOLUTE, IMPELLER BACK SURFACE

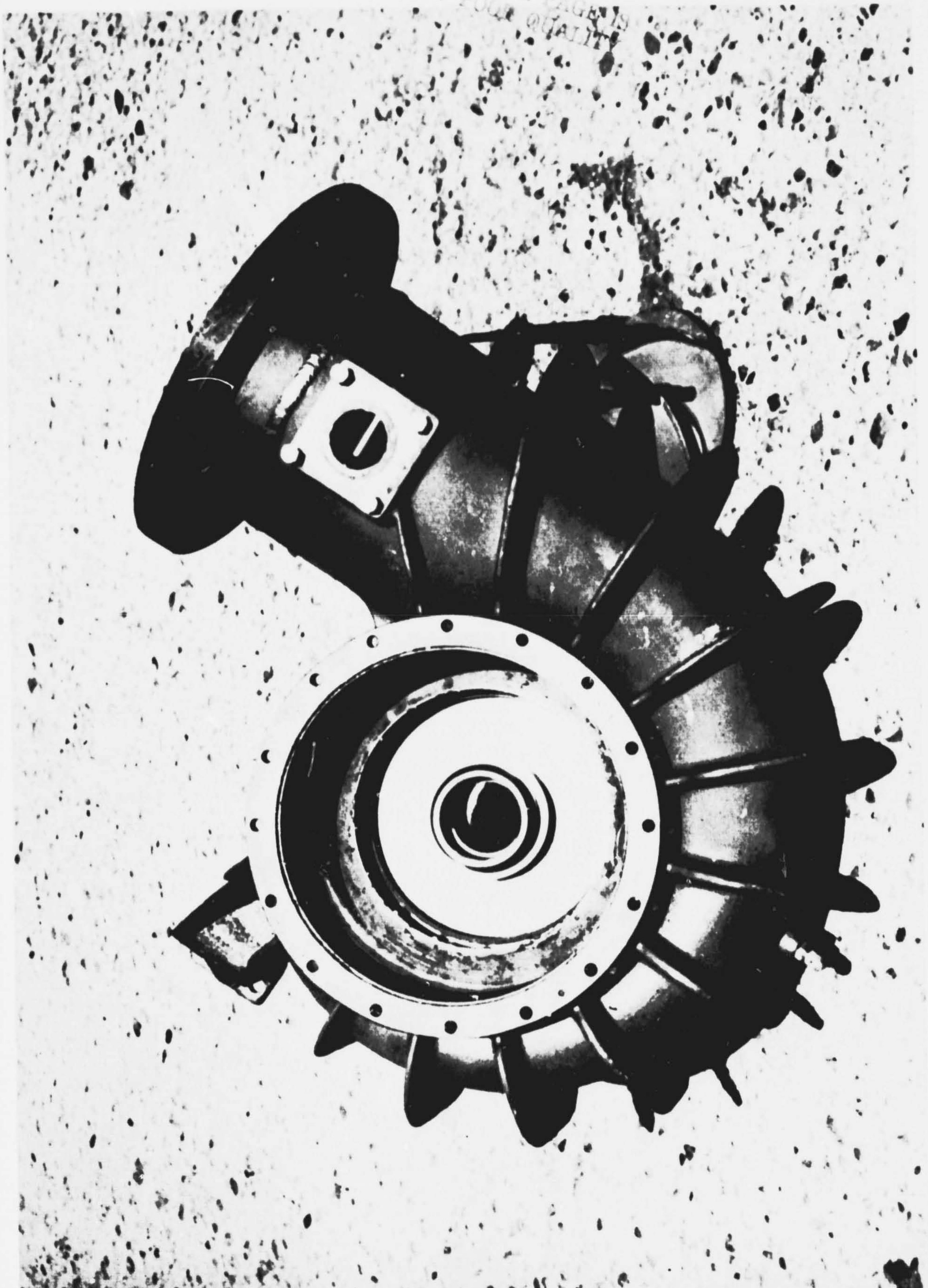

FIGURE 38 - VOLUTE

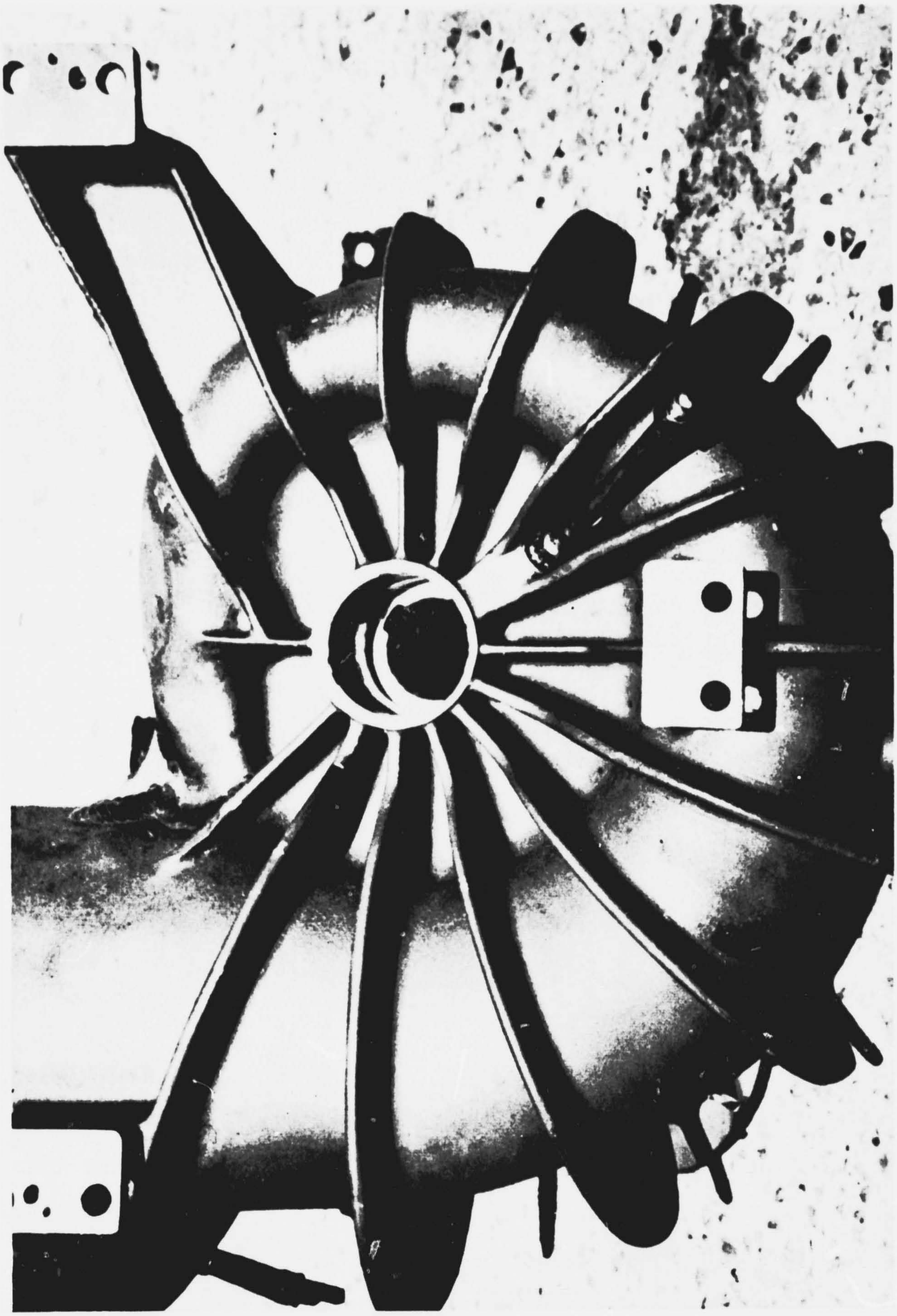

FIGURE 39 - VOLUTE

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APPENDICES

APPENDIX A

Copy No. _____

NORTHERN RESEARCH AND ENGINEERING CORPORATION
219 Vassar Street
Cambridge, Massachusetts 02139

1296 Memorandum M2B
November 16, 1977

LIGHTWEIGHT FIRE-FIGHTING MODULE ACCEPTANCE TEST PROCEDURE

Objective

The objective of the acceptance test is to evaluate the arrangement, equipment, and performance of the fire-fighting module and to verify its ability to fulfill the requirements of the U. S. Coast Guard as set forth in NASA Contract No. NAS8-31977 and Specification No. 22M00516.

Test Procedure Summary

The acceptance test will be performed in Boston by NREC personnel. All test equipment and instrumentation will be provided by NREC. Observations, test conditions, data, and results will be recorded and an acceptance test summary report will be prepared and issued by NREC; copies will be provided to NASA and U. S. Coast Guard. This report will become a part of the final report on the module development program to be issued by NREC.

The static and operational tests to be performed include the following:

1. Inspection of module arrangement, equipment, and weight.
2. Evaluation of module deployment capability.
3. Module operational tests.
   a. Engine startup and pump priming
   b. Pumping system performance
   c. Ancillary equipment tests

These tests are described in detail i subsequent paragraphs.

Inspection of Module Arrangement, Equipment, and Weight

The adequacy and completeness of the module arrangement and equipment will be inspected. This inspection will include, but not necessarily be restricted to, the following items:

1. Adequacy of internal compartments and fittings for stowing and securing equipment.
2. Accessibility of fire-fighting equipment.
3. Accessibility for routine main enance of battery and oil tanks.
4. Completeness of equipment. The contents of the module will be checked against the module material list.
5. Dolly acceptability and module fit on dolly.

Deviations will be logged and included in the Acceptance Test Report.

The module, fully loaded with fuel, oil, and all equipment, will be weighed. The weight must not exceed 3000 lbs.

Evaluation of Module Deployment Capability

The capability of the module to be transported and set up ready to fight a fire will be examined.

1. The module will be lifted with the lift sling to demonstrate sling adequacy.
2. A fork lift truck will be used to lift the module onto the dolly. Module fit on the dolly and attachment to the dolly will be demonstrated.
3. All module and fire-fighting equipment will be removed and set up ready to fight a fire. This will include:
   a. Remove and set up suction pipe.
   b. Open top door and install stacks.
   c. Open control panel door.
   d. Remove and set up module valves, hose, monitors, and nozzles.

4. Deployment of ancillary equipment will also be demonstrated:
   a. Foam injector
   b. Fog nozzle
   c. Booster hose
   d. Protective clothing
5. All equipment will be stowed in module.

Any problems in setting up or stowing equipment will be noted.

Module Operational Tests

The operation of the module and its component parts will be tested for the range of operating conditions likely to be encountered in practice. The following will be required at the test site:

1. A water source.
2. Means of adjusting the vertical distance between the water source and the pump inlet (centerline) over the range from 6 ft. to 24 ft.
3. Instrumentation for measuring pump and engine performance.
   a. Two flow metering devices or a calibrated tank.
   b. Three pressure gauges for measuring pump inlet and outlet pressures, monitor pressures, and engine torque.
   c. A digital counter for reading pump speed.
4. A 55-gal drum of 6 per cent AFFF foam or suitable substitute. (The U. S. Coast Guard will provide this item.)

Preparation

The module will be set up for operation with the suction pipe, exhaust stacks, two monitors, and module valves connected; there will be 25 ft of hose between the module and each monitor. The module valves will be mounted in their normal position. A straight stream nozzle will be mounted on each monitor. Test instrumentation will be installed. The fuel supply, oil levels, and battery condition will be checked in accordance with the operation manual. Suction lift will be set at 12 ft from sea level to pump centerline.

Engine Startup and Pump Priming

Engine startup and pump priming will be initiated by turning the start switch ON and advancing the control lever to ON. The following will be monitored during startup and priming:

1. Engine and pump oil pressures.
2. Engine exhaust temperature.
3. Pump speed.
4. Pump inlet and discharge pressures.

The following will be recorded:

1. Time to lightoff (audible).
2. Time to idle (audible).
3. Time to prime (engine accelerates; pump discharge pressure starts to increase).
4. Time to full pressure.

Pumping System Performance

The module will be set up as described under "Preparation". To demonstrate pumping system performance the following tests will be run:

1. Performance to Coast Guard specification. With both monitor valves open and normal size straight stream nozzles installed the total water flow rate will be measured at a nozzle inlet static pressure of 150 psig or above. The flow rate shall exceed 1500 gpm. The "normal" nozzle size may be selected by NRLC.
2. Reach. With the system operating as in paragraph 1, the water stream reach will be measured.
3. Noise. With the system operating as in paragraph 1, the acoustic noise level at the control panel will be measured.
4. Pressure control system function. With the control system set at ON, the water valves will be throttled in stages from fully open to fully closed. At each stage the pump pressure and flow will be recorded.
5. One sided performance. With one side of the water discharge shut, a large straight stream nozzle installed on the other monitor, and the controller set at MAX, the pressure, flow rate, and reach will be measured.
6. Performance at high lift. Ability of the system to deliver 1500 gpm at 150 psig nozzle inlet static pressure will be demonstrated at the highest lift attainable with the limitations of site and tide, up to 20 ft.

For each of the above tests, the following data will be recorded:

1. Pump speed
2. Water flow rate
3. Suction pressure and lift
4. Discharge pressure
5. Monitor pressures
6. Water temperature
7. Engine torque

Ambient air temperature and pressure will be recorded at the start of testing and each hour thereafter.

Ancillary Equipment Tests

The various items of ancillary equipment supplied with the module will be set up and tested for proper operation.

1. Fog nozzle. Mount on monitor and operate at various settings from fog to stream.
2. Foam inductor. Insert in line and operate with monitor, fog nozzle, and drum of AFFF foam (or equivalent substitute).
3. Booster hose. Deploy and test operation of shut off valve and nozzle.

Report Preparation

A report will be prepared summarizing the data, observations, and results of the acceptance tests. Suggestions for modification or improvement of the module system will be included in this report. Copies of this report will be submitted to NASA and U. S. Coast Guard. This report will become a part of the final report for the fire-fighting module program.

APPENDIX B

Sheet 1 of 2

Date: 12/8/78

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments	Accepted (Initials)
1	Module Arrangement, Equipment, and Weight		
1.1	Internal Stowage of Equipment		
1.2	Accessibility of Equipment		
1.3	Maintenance Access		
1.4	Completeness of Equipment		
1.5	Dolly	✓	
1.6	Weight		
1.6.1	Weight of Module and Dolly	3300	
1.6.2	Weight of Dolly	700	
1.6.3	Net Weight of Module	2600 + Monitors	
2	Module Deployment		
2.1	Sling Lift		
2.2	Fork Lift	✓	
2.3	Equipment Setup and Stowing		
2.3.1	Suction Pipe	✓	
2.3.2	Stacks	✓	
2.3.3	Valves	✓	
2.3.4	Hose	✓	
2.3.5	Monitors (exc. F/g)	✓	
2.3.6	Nozzles	✓	
2.3.7	Foam Injector	✓	
2.3.8	Fog Nozzle	✓	
2.3.9	Booster Hose	✓	
2.3.10	Fire Suits		
3	Preparation for Operation (in accordance with 1296M2B, page 4)		
4	Engine Startup and Pump Priming		
4.1	Time to Light Off, Seconds		
4.2	Time to Idle, Seconds		

Date: 12/8/78

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments	Accepted (Initials)
1	Module Arrangement, Equipment, and Weight		
1.1	Internal Stowage of Equipment		
1.2	Accessibility of Equipment		
1.3	Maintenance Access		
1.4	Completeness of Equipment		
1.5	Dolly		
1.6	Weight		
1.6.1	Weight of Module and Dolly		
1.6.2	Weight of Dolly		
1.6.3	Net Weight of Module		
2	Module Deployment		
2.1	Sling Lift		
2.2	Fork Lift		
2.3	Equipment Setup and Stowing		
2.3.1	Suction Pipe		
2.3.2	Stacks		
2.3.3	Valves		
2.3.4	Hose		
2.3.5	Monitors		
2.3.6	Nozzles		
2.3.7	Foam Injector		
2.3.8	Fog Nozzle		
2.3.9	Booster Hose		
2.3.10	Fire Suits		
3	Preparation for Operation (in accordance with 1296M2B, page 4)		
4	Engine Startup and Pump Priming	[illegible]	
4.1	Time to Light Off, Seconds	3 [illegible]	
4.2	Time to Idle, Seconds	15 [illegible]	[illegible]

Date: 12/8/78

Sheet 1

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments				Accepted (Initials)
4.3	Time to Prime, Seconds	[illegible] from idle				
4.4	Time to Full Pressure, Seconds					
4.5	Suction Lift, Feet	15				
5	Pumping System Performance				[illegible]	
5.1	Monitor Size, Inches	3	3	3	3	
5.2	Nozzles, Number and Diameter, Inches	2-2"	2-2"	2-2"	2-2"	
5.3	Suction Lift, Feet	14	14	14	14	
5.4	Pump Speed, RPM	5680	6080	6360	6480	
5.5	Pump Torque, PSI	60.2	71.3	77.3	80.2	
5.6	(Calculated) Power Input, HP	212.0	268.8	304.9	322.3	
5.7	Pump Discharge Pressure, PSI	123	129	141	146	
5.8	Nozzle Inlet Pressure, PSI (L)	90	100	106	114	
5.9	Nozzle Inlet Pressure, PSI (R)	83	100	106	109	
5.10	(From Nozzle Pressure) Pump Flow Rate, GPM	1790	1920	1977	2032	
5.11	(Calculated) Pump Efficiency, Percentage	64	57	56	57	
5.12	~~Water Temperature, Degrees F~~ ΔH, FT	294.2	308.2	335.5	347.0	
5.13	Reach, Feet	230	230	230	230	
5.14	Noise at Control Panel, Decibels	—	—	—	—	
5.15	Control System Function	OK	OK	OK	OK	
5.16	Monitor Size, Inches	3	3	3	3	
6.	Ancillary Equipment Operation					
6.1	Fog Nozzle					
6.2	Foam Nozzle					
6.3	Booster Hose					

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Date: 12/8/78

Sheet 2

5680
6080
6360
6480

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments				Accepted (Initials)
4.3	Time to Prime, Seconds					
4.4	Time to Full Pressure, Seconds					
4.5	Suction Lift, Feet					
5 .	Pumping System Performance					
5.1	Monitor Size, Inches	3	3	3	3	
5.2	Nozzles, Number and Diameter, Inches	2-1 3/4"	2-1 3/4	2-1 3/4"	2-1 3/4	
5.3	Suction Lift, Feet	14	14	14	14	
5.4	Pump Speed, RPM Panel	5690	6080	6360	6480	
5.5	Pump Torque, PSI	60.8	70.6	77.0	80.8	
5.6	(Calculated) Power Input, HP	214.5	266.2	303.7	324.7	
5.7	Pump Discharge Pressure, PSI	137	160	174	183	
5.8	Nozzle Inlet Pressure, PSI (L)	115	132	146	155	
5.9	Nozzle Inlet Pressure, PSI (R)	110	130	140	145	
5.10	(From Nozzle Pressure) Pump Flow Rate, GPM	1720	1856	1944	1994	
5.11	(Calculated) Pump Efficiency, Percentage	68	68	68	68	
5.12	~~Water Temperature, Degrees F~~ ΔH, Ft	325.4	377.7	409.6	430.0	
5.13	Reach, Feet	—	—	—	282	
5.14	Noise at Control Panel, Decibels	—	—	—	—	
5.15	Control System Function	OK	OK	OK	OK	
5.16	Monitor Size, Inches	3	3	3	3	
6.	Ancillary Equipment Operation Counter	6470				
6.1	Fog Nozzle					
6.2	Foam Nozzle					
6.3	Booster Hose					

Date: 12/8/78

Sheet 3

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments				Accepted (Initials)
4.3	Time to Prime, Seconds					
4.4	Time to Full Pressure, Seconds					
4.5	Suction Lift, Feet					
5	Pumping System Performance					
5.1	Monitor Size, Inches	3	3	3	3	
5.2	Nozzles, Number and Diameter, Inches	2-15/8	2-15/8	2-15/8	2-15/8	
5.3	Suction Lift, Feet	13	13	13	13	
5.4	Pump Speed, RPM panel	5680	6060	6360	6500	
5.5	Pump Torque, PSI	58.3	66.6	74.0	78.0	
5.6	(Calculated) Power Input, HP	205.3	250.3	291.8	314.4	
5.7	Pump Discharge Pressure, PSI	143	167	186	196	
5.8	Nozzle Inlet Pressure, PSI (L)	130	146	160	170	
5.9	Nozzle Inlet Pressure, PSI (R)	122	138	153	162	
5.10	(From Nozzle Pressure) Pump Flow Rate, GPM	1637	1749	1867	1933	
5.11	(Calculated) Pump Efficiency, Percentage	70	71	72	73	
5.12	~~Water Temperature, Degrees F~~ ΔH, Ft	337.6	392.1	435.3	458.0	
5.13	Reach, Feet	—	—	—		
5.14	Noise at Control Panel, Decibels	—	—	—	—	
5.15	Control System Function	OK	OK	OK	OK	
5.16	Monitor Size, Inches	3	3	3	3	
6.	Ancillary Equipment Operation Speedmeter Tormeter	~~5~~	6210	7340 1318	7130 1308	
6.1	Fog Nozzle On panel			→	1300	
6.2	Foam Nozzle					
6.3	Booster Hose					

5680
6040
6360
6480

Date: 12/11/78

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments	Accepted (Initials)
1	Module Arrangement, Equipment, and Weight		
.1	Internal Stowage of Equipment		
1.2	Accessibility of Equipment		
.3	Maintenance Access		
1.4	Completeness of Equipment		
.5	Dolly		
1.6	Weight		
1.6.1	Weight of Module and Dolly		
.6.2	Weight of Dolly		
1.6.3	Net Weight of Module		
2	Module Deployment		
2.1	Sling Lift		
2.2	Fork Lift		
2.3	Equipment Setup and Stowing		
2.3.1	Suction Pipe		
2.3.2	Stacks		
2.3.3	Valves		
2.3.4	Hose		
2.3.5	Monitors		
2.3.6	Nozzles		
2.3.7	Foam Injector		
2.3.8	Fog Nozzle		
2.3.9	Booster Hose		
2.3.10	Fire Suits		
3	Preparation for Operation (in accordance with 1296M2B, page 4)	Done	
4	Engine Startup and Pump Priming		
4.1	Time to Light Off, Seconds	2	
4.2	Time to Idle, Seconds	15	

Date: 12/11/78

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments						Accepted (Initials)
4.3	Time to Prime, Seconds	90						
.4	Time to Full Pressure, Seconds	95						
4.5	Suction Lift, Feet	12.5						
5	Pumping System Performance							
5.1	Monitor Size, Inches	3	3	3	3	3	3	
5.2	Nozzles, Number and Diameter, Inches	2-1 3/4	2-1 3/4	2-1 3/4	2-1 3/4	2-2	2-1 3/4	
5.3	Suction Lift, Feet	12.5	12.5	12.5	12.5	13	13	
.4	Pump Speed, RPM	5680	6080	6360	6600	6480	6480	
5.5	Pump Torque, PSI	—	—	—	—	—	—	
.6	(Calculated) Power Input, HP	—	—	—	—	—	—	
5.7	Pump Discharge Pressure, PSI	138	165	178	192	152	185	
5.8	Nozzle Inlet Pressure, PSI (L)	110	131	142	155	110	150	
5.9	Nozzle Inlet Pressure, PSI (R)	115	134	150	160	118	155	
5.10	(From Nozzle Pressure) Pump Flow Rate, GPM	—	—	—	—	—	—	
5.11	(Calculated) Pump Efficiency, Percentage	—	—	—	—	—	—	
5.12	Water Temperature, Degrees F	—	—	—	—	—	—	
5.13	Reach, Feet	230	250	250	250	230	250	
5.14	Noise at Control Panel, Decibels	—	—	—	—	—	—	
5.15	Control System Function	OK	OK	OK	OK	OK	OK	
5.16	Monitor Size, Inches							
6.	Ancillary Equipment Operation							
6.1	Fog Nozzle							
6.2	Foam Nozzle							
6.3	Booster Hose							

Date: 12/11/78

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments	Accepted (Initials)
4.3	Time to Prime, Seconds		
4.4	Time to Full Pressure, Seconds		
4.5	Suction Lift, Feet		
5	Pumping System Performance		
5.1	Monitor Size, Inches F/G/St	4/3	
5.2	Nozzles, Number and Diameter, Inches	2-3/4	
5.3	Suction Lift, Feet	20+	
5.4	Pump Speed, RPM		
5.5	Pump Torque, PSI	DID	
5.6	(Calculated) Power Input, HP		
5.7	Pump Discharge Pressure, PSI	NOT	
5.8	Nozzle Inlet Pressure, PSI (L) Stang 3"	PRIME	
5.9	Nozzle Inlet Pressure, PSI (R)	— — — —	
5.10	(From Nozzle Pressure) Pump Flow Rate, GPM		
5.11	(Calculated) Pump Efficiency, Percentage		
5.12	Water Temperature, Degrees F		
5.13	Reach, Feet		
5.14	Noise at Control Panel, Decibels		
5.15	Control System Function		
5.16	Monitor Size, Inches		
6.	Ancillary Equipment Operation		
6.1	Fog Nozzle		
6.2	Foam Nozzle		
6.3	Booster Hose		

Date: 12/12/78

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments				Accepted (Initials)
.3	Time to Prime, Seconds					
.4	Time to Full Pressure, Seconds					
4.5	Suction Lift, Feet FIBERGLASS	MONITOR CHECK				
5	Pumping System Performance					
.1	Monitor Size, Inches	3/4	3/4	3/4	3/4	
5.2	Nozzles, Number and Diameter, Inches (Same)	2-2	2-1¾	2-1¾	2-1¾	
.3	Suction Lift, Feet	12.5	12.5	12.5	12.5	
5.4	Pump Speed, RPM	6360	5680	6080	6360	
.5	Pump Torque, PSI	—	—	—	—	
.6	(Calculated) Power Input, HP	—	—	—	—	
5.7	Pump Discharge Pressure, PSI	146	138	165	177	
.8	Nozzle Inlet Pressure, PSI (L) 3"St/2"N	105	115	132	140	
5.9	Nozzle Inlet Pressure, PSI (R) 4"FG/2"N	—	—	—	—	
5.10	(From Nozzle Pressure) Pump Flow Rate, GPM	—	—	—	—	
5.11	(Calculated) Pump Efficiency, Percentage	—	—	—	—	
5.12	Water Temperature, Degrees F	—	—	—	—	
5.13	Reach, Feet	250	250	250	250	
5.14	Noise at Control Panel, Decibels					
5.15	Control System Function					
5.16	Monitor Size, Inches					
6.	Ancillary Equipment Operation					
6.1	Fog Nozzle					
6.2	Foam Nozzle					
6.3	Booster Hose					

Date: 12/16/78

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments				Accepted (Initials)
4.3	Time to Prime, Seconds					
4.4	Time to Full Pressure, Seconds					
4.5	Suction Lift, Feet					
5	Pumping System Performance	High IDLE		AT STOP		Idle
5.1	Monitor Size, Inches	3	3	3	3	3
5.2	Nozzles, Number and Diameter, Inches	2-1¾	2-1¾	2-1¾	2-1¾	2-1¾
5.3	Suction Lift, Feet	17'6"	17'8"	17'10"	18'	18'6"
5.4	Pump Speed, RPM	4480	5680	6080	4860	3200
5.5	Pump Torque, PSI	—	—	—	—	—
5.6	(Calculated) Power Input, HP	—	—	—	—	—
5.7	Pump Discharge Pressure, PSI	80	130	140	102	43
5.8	Nozzle Inlet Pressure, PSI (L)	74	110	120	85	37
5.9	Nozzle Inlet Pressure, PSI (R)	60	105	115	82	30
5.10	(From Nozzle Pressure) Pump Flow Rate, GPM	—	—	—	—	—
5.11	(Calculated) Pump Efficiency, Percentage	—	—	—	—	—
5.12	Water Temperature, Degrees F	—	—	—	—	—
5.13	Reach, Feet	144	283	204	156	—
5.14	Noise at Control Panel, Decibels	—	—	—	—	—
5.15	Control System Function	OK	ok	OK	ok	OK
5.16	Monitor Size, Inches	3	3	3	3	3
6.	Ancillary Equipment Operation	~~1~~	~~3~~	~~4~~	~~2~~	—
6.1	Fog Nozzle					
6.2	Foam Nozzle					
6.3	Booster Hose					

Date: 1/12/79

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments	Accepted (Initials)
1	Module Arrangement, Equipment, and Weight		
.1	Internal Stowage of Equipment		[illegible]
1.2	Accessibility of Equipment		[illegible]
.3	Maintenance Access		[illegible]
1.4	Completeness of Equipment		[illegible]
.5	Dolly		[illegible]
.6	Weight		
.6.1	Weight of Module and Dolly	3400	[illegible]
.6.2	Weight of Dolly	700	[illegible]
1.6.3	Net Weight of Module	2700	[illegible]
-	Module Deployment		
2.1	Sling Lift		[illegible]
.2	Fork Lift		[illegible]
2.3	Equipment Setup and Stowing		[illegible]
.3.1	Suction Pipe		[illegible]
2.3.2	Stacks		[illegible]
..3.3	Valves		[illegible]
2.3.4	Hose		[illegible]
.3.5	Monitors	(Fiberglass monitors to be repressure	[illegible]
.3.6	Nozzles	tested & then provided to USCG)	[illegible]
.3.7	Foam Injector		[illegible]
.3.8	Fog Nozzle		[illegible]
2.3.9	Booster Hose		[illegible]
2.3.10	Fire Suits		[illegible]
3	Preparation for Operation (in accordance with 1296M2B, page 4)		
4	Engine Startup and Pump Priming		[illegible]
4.1	Time to Light Off, Seconds	3	[illegible]
4.2	Time to Idle, Seconds	12	[illegible]

Date: 1/12/79

DATA SHEET

MODULE ACCEPTANCE TEST

Item No.	Description	Results and Comments					Accepted (Initials)
4.3	Time to Prime, Seconds	70					[illegible]
4.4	Time to Full Pressure, Seconds	-					
4.5	Suction Lift, Feet	14	1		2	3	[illegible]
5	Pumping System Performance	IDLE	FULL	3/4	FULL	FULL	
5.1	Monitor Size, Inches	4	4	4	4	4	
5.2	Nozzles, Number and Diameter, Inches	1 3/4	1 3/4	1 3/4	1 3/4	1 3/4	[illegible]
5.3	Suction Lift, Feet	14	14	14	15.5	16.5	ATP
5.4	Pump Speed, RPM	2950	6080	5680	6080	6080	[illegible]
5.5	~~Pump Torque, PSI~~ EGT °F	925	1060	1000	1240	1240	[illegible]
5.6	(Calculated) Power Input, HP Batt, amp	45	32	32	32	32	[illegible]
5.7	Pump Discharge Pressure, PSI	40	152	134	149	149	
5.8	Nozzle Inlet Pressure, PSI (L)	—	—	—	—	—	
5.9	Nozzle Inlet Pressure, PSI (R)	—	—	—	—	—	
5.10	~~(From Nozzle Pressure) Pump Flow Rate, GPM~~ Pump oil Press, psi	112	122	121	122	122	
5.11	(Calculated) ~~Pump Efficiency, Percentage~~ Eng Oil Press, psi	116	115	118	118	118	
5.12	Water Temperature, Degrees F						
5.13	Reach, Feet		Note	EGT	EGT		
5.14	~~Noise at Control Panel, Decibels~~		not	right	OK		
5.15	~~Control System Function~~			SHUT	SHUT	SHUT	
5.16	~~Monitor Size, Inches~~			Down	Down	Down	
6.	Ancillary Equipment Operation						
6.1	Fog Nozzle						[illegible]
6.2	Foam Nozzle						[illegible]
6.3	Booster Hose						[illegible]

APPENDIX C

PUMP DISASSEMBLY, INSPECTION, AND REBUILD

(June 11-15, 1979, in Mobile)

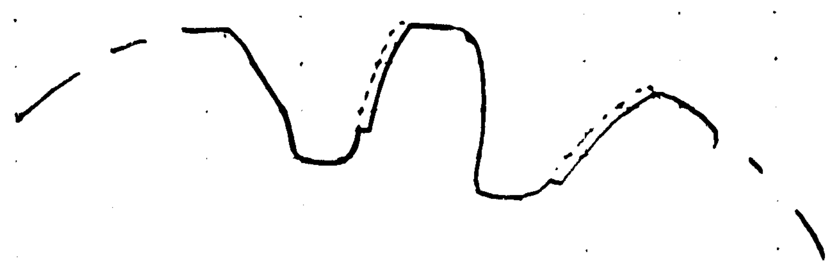
Introduction

After approximately 130 hours of endurance and operational testing, the firefighting pump was removed from the module for teardown, inspection, and refurbishing. The inspection results are reported below.

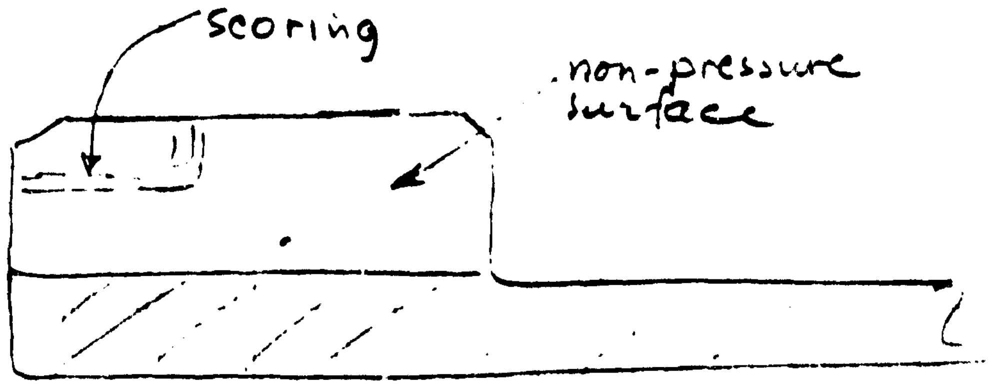
Inspection of Pump Parts

Quill Shaft

The pump end of the quill shaft was in excellent condition and showed no appreciable wear. The engine end of the quill shaft was severely worn: the pressure faces of the spline teeth were uniformly worn and polished from the tips to about 0.030 inch from the root fillet (see sketch below). There was no evidence of wear on the engine spline.



About one third of the spline teeth on the engine end had scoring on the non-pressure side near the end of the spline (see sketch on the next page).

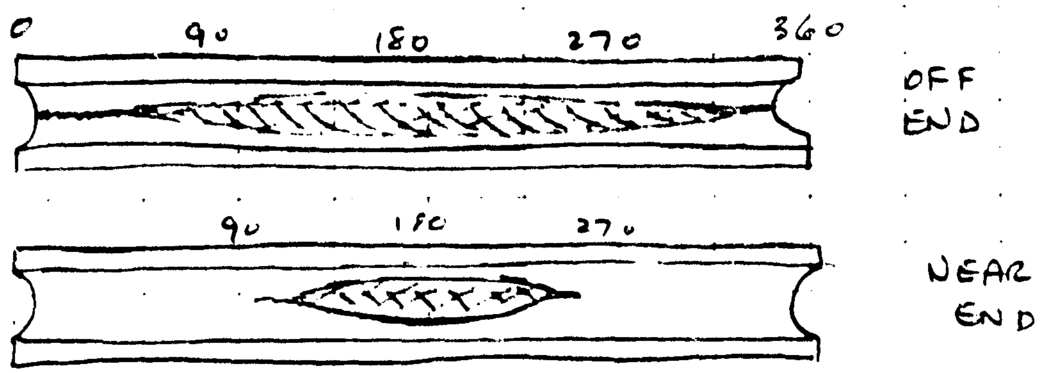


Spline Coupling

This part appeared in perfect condition with no appreciable wear.

Bearings, Main Impeller Shaft

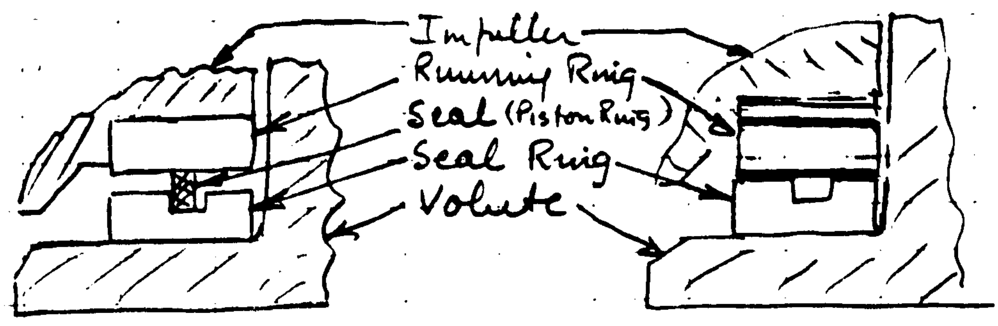
The bearings on the main impeller shaft were severely worn. The inner races showed deep impact-type surface wear. On one inner race this extended over almost 360 degrees, with the most severe wear over about 150 degrees. This bearing was mounted on the shaft farthest from the impeller. The second inner race was damaged only over a 120-degree arc; this race was mounted nearest the impeller. The wear patterns suggest a severe radial load rotating with the impeller, possibly from imbalance. They do not suggest a thrust load. The outer races were lightly worn over their entire periphery. Wear patterns on the inner races are sketched below and photographed in Figures 29 and 30.



Most of the balls were in good condition. Two or three balls in each bearing showed a few pits or scratches. One ball in the off-end (away from the impeller) bearing had a single badly damaged spot about 1/8-inch across. This spot looked as though a chip had been knocked off the surface.

Impeller Seal (Piston Ring)

The main impeller seal (piston-ring type) was severely damaged. This seal consists of a stainless-steel seal ring mounted on the volute, a stainless-steel running ring mounted in the impeller, and a Teflon-carbon piston ring that rides in a groove in the seal ring. Upon disassembly, it was found that the running ring had become detached from the impeller and (apparently) attached to the seal ring; it had worn the impeller sufficiently to open a clearance of approximately 0.020 inch. The piston ring had completely disintegrated and disappeared. Both the stainless rings and the impeller were corroded and stained. See sketch below and Figures 31, 32, 33.



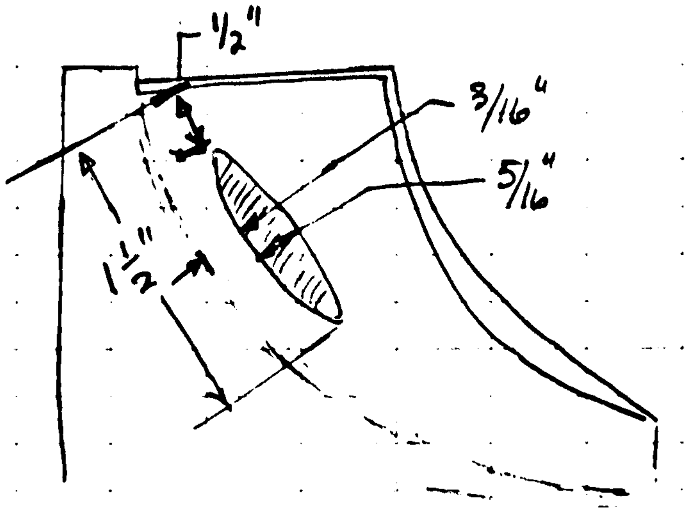
As Installed — At Disassembly

It is inferred that the running ring had been stationary for many hours of operation. Wear marks on both impeller and running ring were obliterated by corrosion.

Main Impeller

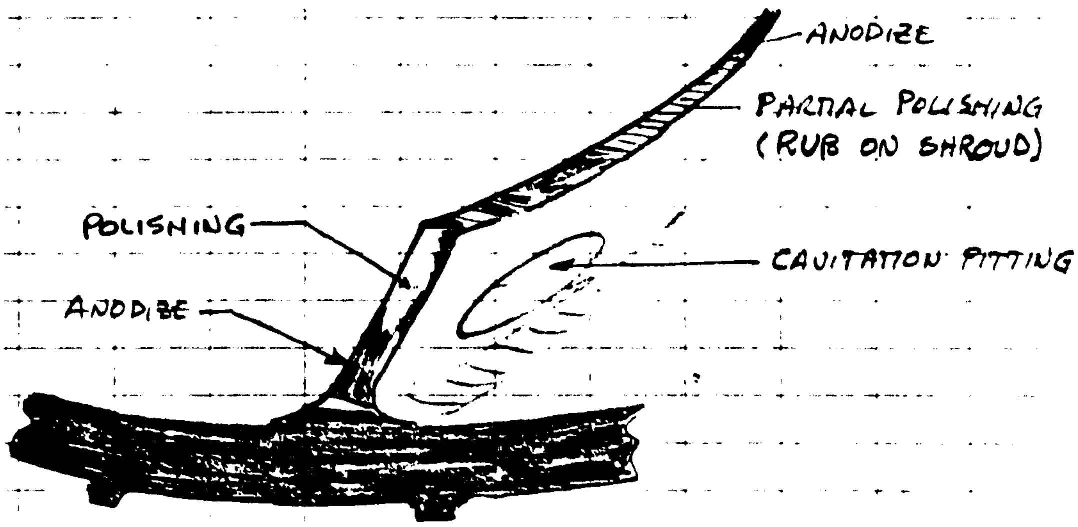
The main impeller was in generally excellent condition, with the following exceptions:

1. Wear of the running-ring bore associated with the seal failure described above (Figs 31, 32, and 33).
2. Very slight scoring of the shroud. This was so minor as to leave the anodized coating intact, with minor exceptions.
3. A small area of cavitation pitting on the pressure surface of each blade about an inch from the trailing edge and half an inch from the hub (see sketch below and Fig 34).



Cavitation Pitted Region

4. Partial polishing of blade tips (cylindrical surface), sufficient to remove anodizing (see sketch below and Fig 34).



Typical Impeller Appearance

Main Impeller Shaft and Gearbox

The main impeller shaft, input (sun) gear, idler gears, idler bearings, idler gear carrier, and output (ring) gear were all in excellent condition with no signs of wear or corrosion. (The idler gears were not disassembled from the carrier; needle bearings were inspected by feel only.) See Figure 35.

Inducer Shaft, Bearings, and Seals; Front Bearing Housing

The inducer shaft, bearings, and seals appeared to be in excellent condition when inspected by feel without disassembly. The front bearing housing was in excellent condition with no evidence of wear or corrosion.

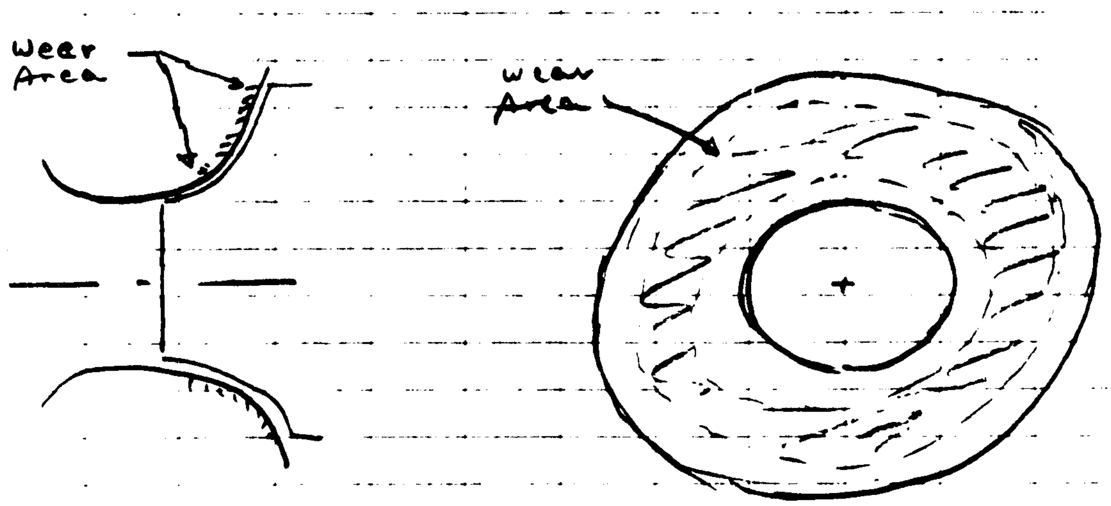
Inducer Impeller

The inducer impeller was in excellent condition. There was no evidence of cavitation damage. The anodized coating was everywhere intact.

Inducer Housing

There was surface abrasion to the inducer housing in two locations: on the inducer shroud near the inlet to the inducer blading and on the main impeller shroud near the impeller discharge. The abrasion in the inducer shroud was damage sustained during endurance testing at NREC in September, 1978, when two inducers developed cracked blades and rubbed the shroud. This abrasion did not appear to worsen during the Coast Guard's test program.

The abrasion on the main impeller shroud covered approximately 1 1/2 inches along the shroud from the impeller tip inwards and was nowhere more than a few thousandths of an inch deep. This abrasion was probably associated with and a consequence of the bearing wear described above. See the sketch on the following page and Figure 36.



Volute

The pump volute appeared to be in good condition. The anodized coating was intact. There was some minor evidence of corrosion pitting on a microscopic scale (Fig 37). The bearing bore proved to be undersize by approximately 0.005 inch at the location of the inner main impeller bearing. As this condition did not exist at the time of assembly, it is inferred that heat developed in the seal rings at the time of the seal failure described above may have caused the aluminum to creep under pressure from the shrink-fitted seal ring. When the seal ring was removed from the volute, some distortion of the faying surface was noted, supporting this conjecture. Other views of the volute are shown in Figures 38 and 39.